Dear Editor,

Thank you very much for your consideration of our paper for the potential publication and your suggestions about the major revision. We have carefully revised the manuscript following comments point-by-point. We prepared three documents as requested: (1) a point-to-point reviewer response document including original comments/questions, our response, and corresponding revisions made in the manuscript, (2) a track-change manuscript showing all the detailed modifications in the manuscript, and (3) a clear manuscript after revision.

Again, we appreciate your kind help in the reviewing and revision process. We look forward to further updates from you.

Warm regards,
Xianwu Shi
On behalf of the co-authors

Responses to Reference Report #1

The paper aims at quantifying the inundation range and water depth distribution due to storm surges for different typhoon scenarios for the Pingyang County in China. The typhoon scenarios are constructed in a consistent way to reflect variations in tracks and intensity. The storm surges are estimated with the hydrodynamical model. In combination with the peak river runoff values the water level scenarios are used for the estimation of the coastal flooding magnitude in case of a seawall breach. The study provides an insight into the spatial distribution of the areas potentially endangered by the typhoon related flooding. It can be helpful for further hazard and risk assessments for urban planning, emergency procedures or insurance. The paper is well structured and mostly easy to follow. Here are some points requiring clarification and some suggestions:

Response: We greatly appreciate your kind help in reviewing the manuscript and all constructive comments. We substantially revised the paper based on these comments.

Section 3.1:

Concerning the data sources and DEM, I agree with the first reviewer. Please include the response you gave, at least partially, into the paper.

Response: Thanks for your suggestion. we have modified Fig 1 as bellow:

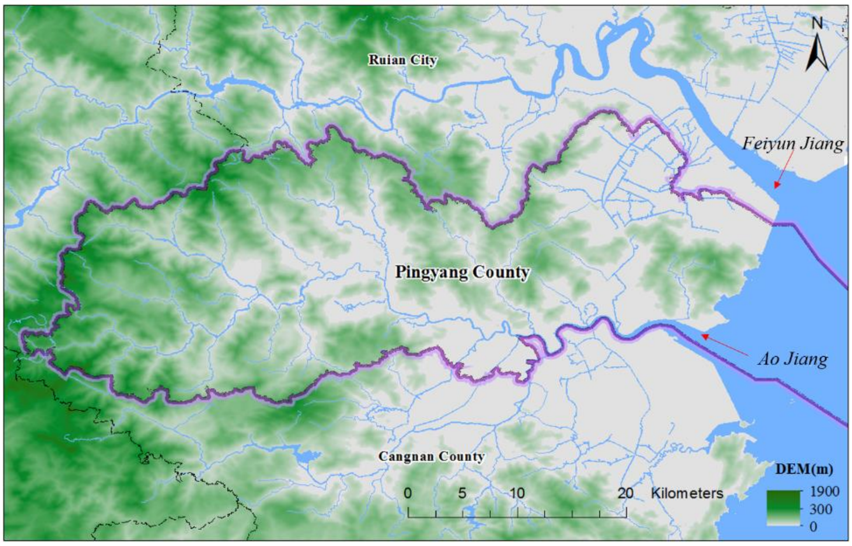


Fig. 1 case study area

Fig. 2 in the review response: Please include this figure into the paper with (1) better quality (2) color code for the land elevation, so the orography of the potentially flooded area can be deduced.

Response: Thanks for your suggestion. we have modified Fig. 2b and Fig. 2c according to your advice.

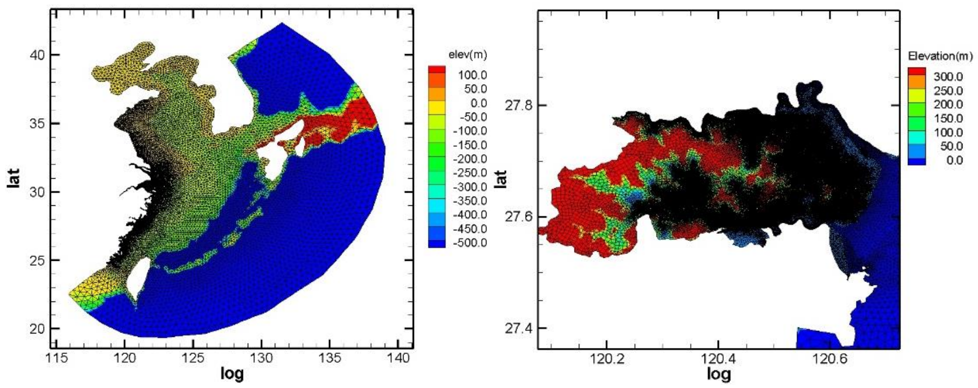


Fig. 2b mesh of the numerical model in the offshore area.Fig. 2c refined mesh in Pingyang County

Section 3.3 and Tables 1 and 2:

1） 139 – table content is specified as “error statistics”. (1) Are these values the differences between two values: observed and modeled max high water (or max storm surge) for each typhoon and location? (2) What are the “average errors” discussed in lines 142-150 and shown in the last column and line of the Tables? These values seem not to be the average (mean) of the values in the Tables. E.g. Table 1, event 9015 – Average value 8 is not equal to the mean of (3, 2, -23), similar is true for many other lines and columns. Please either specify in the text how these “average” values were obtained or correct the average values in the Tables and discussion in the Section 3.3 accordingly.

Response: Thanks for noting this error. we have modified the manuscript according to your advice.

(1) These values are the differences between observed and modeled max high water (or max storm surge) for each typhoon and location.
(2) The “average errors” indicates the mean absolute error of the differences between observed and modeled value in each station, and we have corrected the value in Table 1 and 2.

2） 142-143: the locations of the tidal stations on the map (either Fig. 1 of figure with DEM) would be helpful. They could also help to understand the significant differences in the storm surges on Fig. 4.

Response: Thanks for your suggestion. A new map that the location of the tidal stations have been added was presented in the revised manuscript as below:

Fig.3 the distribution of tidal station along the coastal Zhejing Province

3） 144: “storm surge high tide” please reformulate because by definition “surge” is a residual of water level and the tide and has no tidal component.

Response: Thanks for your suggestion. “storm surge high tide” has been changed to “water level” in the revised manuscript.

4） 146: “10% of the maximum storm surge” – what is the value of maximum storm surge and which maximum storm surge is meant here? Is it at any particular location or/and event or averaged maximum? Please specify in the text. Also, if the 10% is about 10cm as mentioned in the text, then the maximum storm surge should be about 1m, however at the Fig. 4 there are storm surges reaching over 3m.

Response: Thanks for your comments. the maximum storm surge means the max value for each tidal station in a typhoon storm surge event process. To avoid ambiguity, the sentences”10% of the maximum storm surge” in the paper has be deleted.

Sections 3.3:

The information about the tidal signal used at the open boundaries during validation is missing. Approximate tidal range at the coast is worth mentioning in this section because the discussed errors of 15-30 cm have different weight when they occur for the tidal range of e.g. 1m or 6m. Also, how the astronomical tides were estimated for calculation of storm surges is interesting, especially in connection with Fig.3 and Fig.4.

Response: Thanks for your comments and question. The Global Ocean Tide Model of TPXO 6.2 developed by Oregon State University was used as tidal signal at the open boundaries. We have added the information that the tidal range along Pingyang coast is about 4.45m in the revised manuscript. The monthly averaged water levels of the previous 19 years during June–October at the Dongtou tidal stations in the study area were selected as the astronomical tide levels to simulate the inundation range and water depth of storm surges under different typhoon intensities in this study. In Fig.3 and Fig.4, the astronomical tides are computed based on observational water level data using harmonic analysis method during validation, and we get storm surges by the simulated water level minus to the astronomical tidal value.

1) Fig. 3 and Fig. 4: Please include the dates on the x-axis additionally to the time. The axis are different between Fig. 3 and Fig. 4 and it is difficult to recognize the corresponding water level and storm surge. For example, for Ruian on Fig.4 there is a storm surge of 3m, however on Fig.3 for the same location and same typhoon it is really hard to deduce when such high surge has taken place.

Response: Thanks for your suggestion. We have modified Fig 3 and Fig 4 in the revised manuscript.

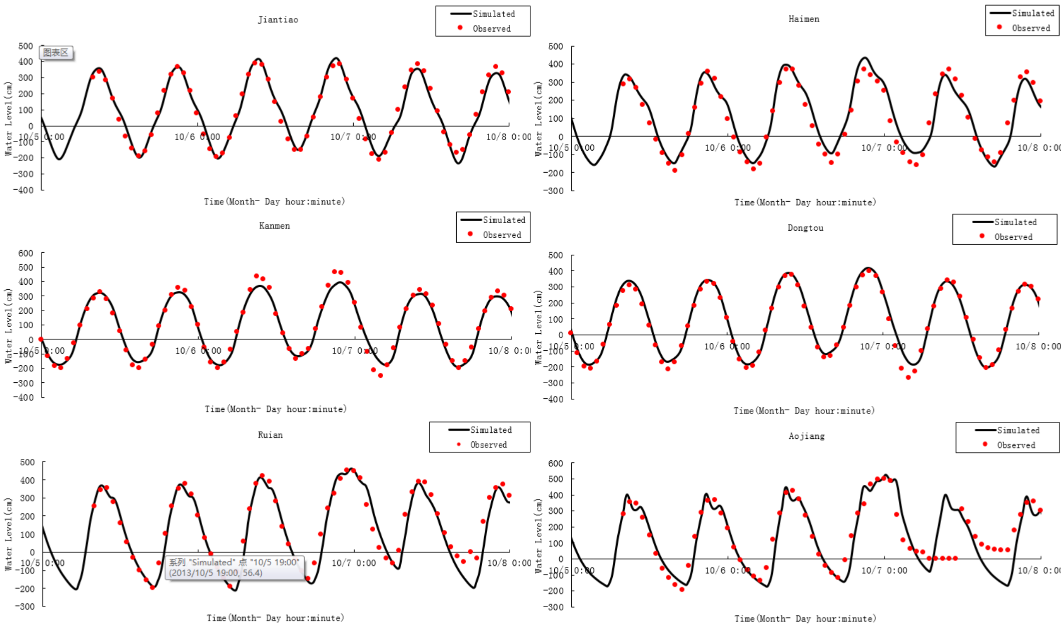
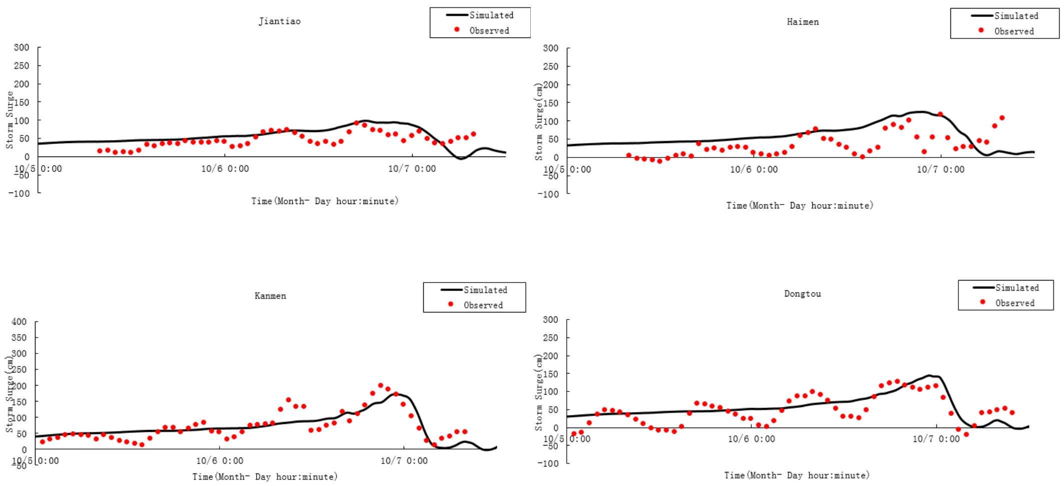


Fig. 4 Verification of the water level for tidal stations affected by the storm surge caused by Typhoon Fitow (No. 1323)



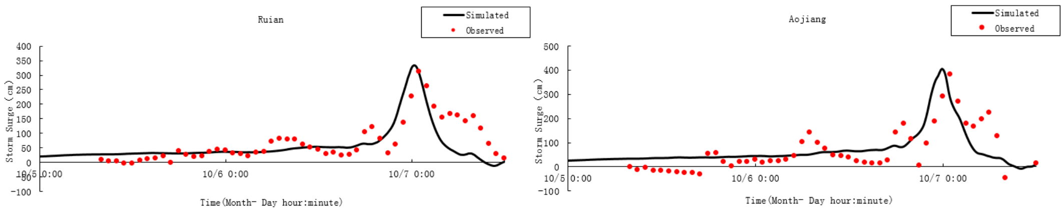


Fig. 5 Verification of the storm surge for tidal stations affected by the storm surge caused by Typhoon Fitow (No. 1323)

2）189: Please provide a quantitative example of the highest water level during this typhoon for any location of your choice in the area of investigation.

Response: Thanks for your suggestion. the tidal level at Ao Jiang Station caused by Typhoon Fred was presented in the manuscript as below:

This typhoon landed at the time of the highest astronomical tide and it generated the highest tide level ever recorded in the coastal area, causing the tidal level at Ao Jiang Station up to 6.56m.

3）197-198: (1) does “constant direction of movement” mean that the modified typhoon moves in a straight line? If not, please reformulate. If yes, please explain how this constant direction corresponds to original typhoon track. (2) “track… was translated to the landing site…” – meaning the track was shifted so that landing points coincide? (3) the map with the original tracks of the two typhoons and the “designed typhoon” track described in the line 202 would be very helpful here

Response: Thanks for your suggestion and comments.

(1) “constant direction of movement” mean that the designed typhoon” track move in the same direction and are parallel to the track of 0608 “Saomei”.

(2) yes, “track… was translated to the landing site…” means the track was shifted so that landing points coincide.

(3）the map with the original tracks of the two typhoons and the “designed typhoon” track were presented in the revised manuscript as shown as bellow:

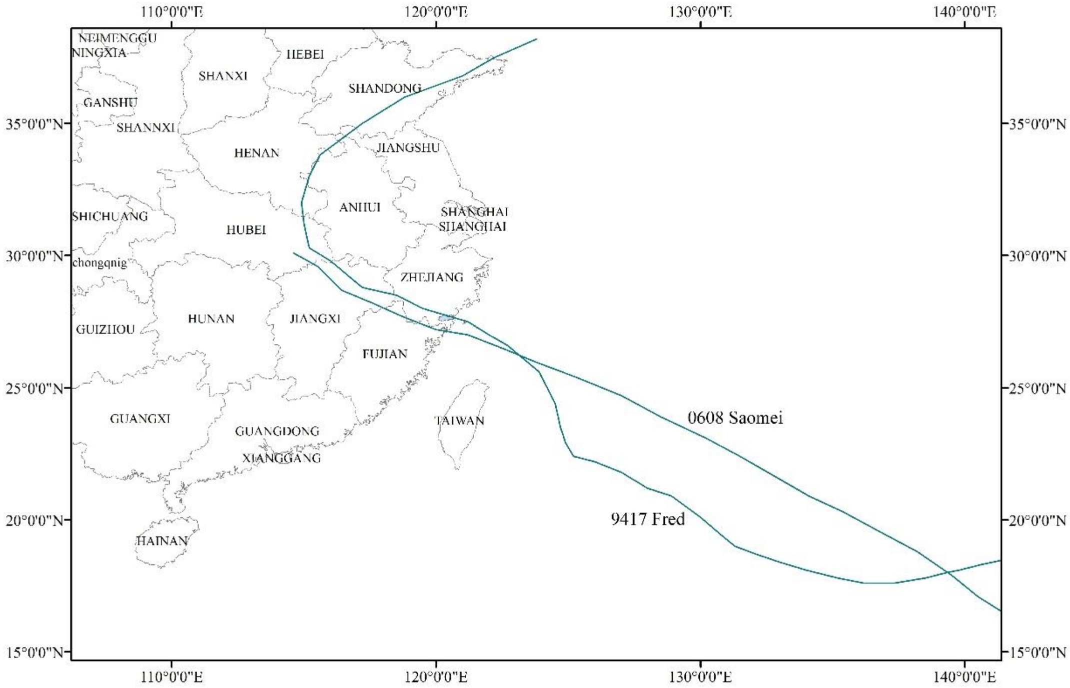


Fig 6 Typhoon track of 9417 “Fred” and 0608“Saomei”

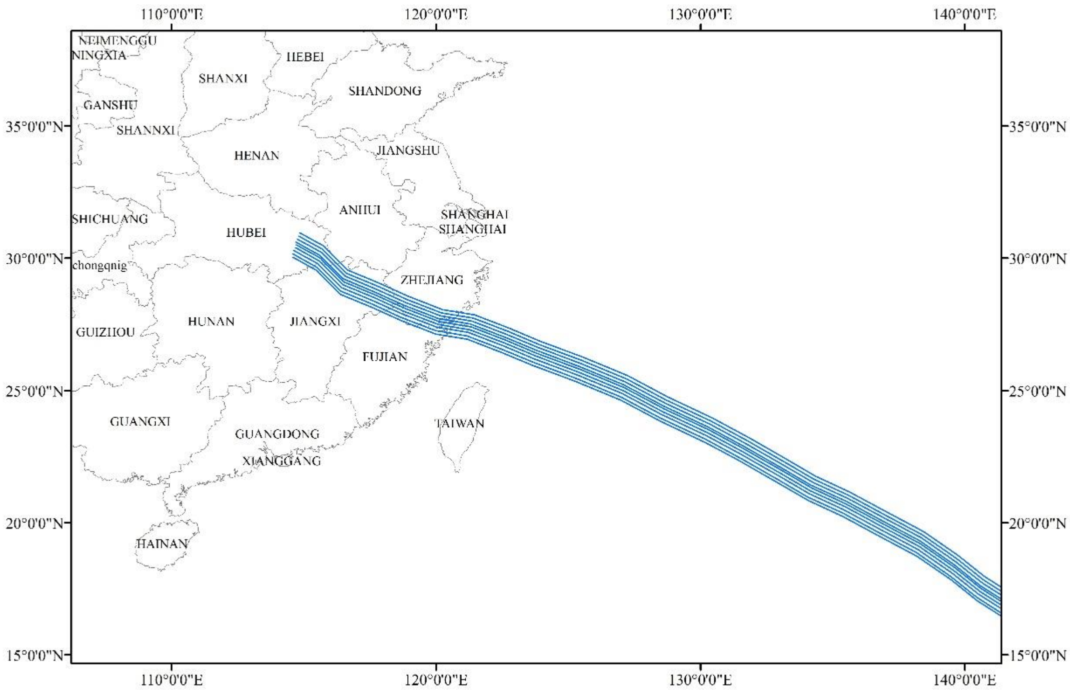


Fig 7 “designed typhoon” track set over Pingyang County

4）215: “36 and 36 km” please correct

Response: Thanks for noting this. We have carefully checked it, and there is nothing wrong.

Where the central air pressure (P_0) was set to 915 or 925 hPa, the radius of maximum wind speed (R) both obtain the value of 36 km computing by Formula 4.

5）220: change “coupled” to “linearly added” - as far as I understood, the high tide values were linearly added to the peak surge heights at the coast

Response: Thanks for your suggestion. The coupling of the astronomical tide and the storm surge was performed for simulation of the total elevation and range of inundation, and the high tide values were not linearly added to the peak surge heights at the coast.

6）229: “peak flow in an estuary has no obvious influence…” - Does it mean the peak flow does not influence water levels during the typhoon OFF the estuary or IN the estuary? If the former, please add this to the sentence. If the later, then it contradicts with the next two sentences, where it is stated that “storm surge-runoff interaction…increases the tidal level…”.

Response: Thanks for your suggestion. I am sorry that there is a typo mistake in this sentence. This sentence has been modified as below in the revised manuscript:

The peak flow in an estuary has obvious influence on the high-water level during the passage of a typhoon (Sun et al., 2017).

7）245-246: Where the wave overtopping rate came from in the numerical simulations for this study? Was the wave model additionally used to estimate the overtopping? Or how the wave overtopping was found based on the results from the storm surge model? Please specify.

Response: Thanks for your question. The typhoon-astronomical-flood-wave coupled numerical model was used to perform the storm surge simulation in this study (Chen et al, 2019). Waves caused by typhoon are simulated by SWAN model, which can describe the evolution of wave fields under specific wind, flow and underwater terrain conditions in shallow waters. The governing equation is as follows.

$$\frac{\partial}{\partial_t}N+\frac{\partial}{\partial_x}C_xN+\frac{\partial}{\partial_y}C_yN+\frac{\partial}{\partial_\sigma}C_\sigma N+\frac{\partial}{\partial_\theta}C_\theta N=\frac{S}{\sigma}$$

In the equation, N is wave action, σ is relative frequency of waves, θ is wave direction, and S is source item. C_x and $C_y$are wave propagation speed in x and y direction, respectively. $C_\sigma$is propagation speed of wave action in frequency space, and C_θ is the propagation speed of wave action in wave direction space.

Based on the wave elements and the structural parameters of the seawall, the overtopping discharge is calculated by the empirical formula. In the simulation of dike-breaching, the varying dike top elevation is applied according to overtopping discharge to simulate the process of dike-breaching.

Discussion: Discuss the limitations and sources of uncertainty originating in e.g. linear combination of averaged high tides instead of dynamically simulated surge and tide with their interaction; simplified seawall collapse scenarios and how this can affect the estimates of inundated areas (for example, in this study inundation is independent on the duration of the storm surge event).

Response: Thanks for your suggestion. According to your advice, the sections of Discussion and Conclusion has been modified in the revised manuscript. The limitation and sources of uncertainty of this study have been modified in the revised manuscript as below:

This study contributed to the methodology of storm surge inundation simulation caused by different intensities of typhoon. A high-precision numerical model for simulating storm surges was established and validated by observational data and field-surveying inundated areas after. Using these key parameters including typhoon tracks, radius of maximum wind speed, astronomical tide, and upstream flood runoff as driving factors, the inundation extents and depths in Pingyang County corresponding to the storm surges under different typhoon intensity scenarios were simulated in combination with the storm surge numerical model. The obtained results could serve as a basis for developing a methodology for storm surge disaster risk assessment in coastal areas. The study provides an insight into the spatial distribution of the areas potentially endangered by the typhoon related flooding. It can be helpful for further hazard and risk assessments for urban planning, emergency procedures and insurance.

The inundation extent of a storm surge is related to many factors (Petroliagkis, 2018). In this study, the process of inundation is independent on the duration of the storm surge event, and the seawall collapse scenarios is simplified in a sudden, which could increase the inundation range of the simulated result. The water level in the towns of Shuitou and Xiaojiang in Pingyang County is mainly caused by the upstream flood of the Aojiang River. Consequently, the inundation in these two areas is directly related to upstream flood runoff. The impact of the upstream flood was only considered as the average of the flood peak flow during the storm surge in this study. The water level and inundation areas caused by the large astronomical tide due to the superposition of the extreme flood scenarios might be more unfavourable than the simulated storm surge with the superimposed average of the flood peak runoff, which might result in uncertainty in the calculation results. We will analyze the quantitative response relationship between typhoon intensity at landfall and upstream flood runoff, and propose a quantitive method for setting flood runoff upstream of the estuary area in the further research.

This paper presents a deterministic method for setting key parameters under typhoon intensity scenarios assuming that these factors (e.g., typhoon track, radius of maximum wind speed, astronomical tide, and upstream flood runoff) are independent. However, any correlation between these parameters is ignored. The occurrence probability of parameter combinations is difficult to evaluate. The joint probability method is an efficient way to determine the base flood elevation due to storm surge (Yang et al. 2019), and the joint probability among these factors could be established (e.g., using the Copula method) to calculate the occurrence of extreme storm surge events.

Responses to Reference Report #2

This work focuses on Simulating storm surge-induced inundation under different typhoon intensity scenarios. Although the results are within the scope of NHESS, scientific discourses on the coastal storm surge are insufficient. My suggestion is a major revision.

Response: Thanks for your comments. We substantially revised the paper based on these comments.

Comments:

1. It seems the "wave setup" is excluded in your modeling results. In my opinion, the "wave setup" is sometimes dominating the storm surge. The effect of "wave setup" is more significant than "air pressure" and even "wind stress", depended on the bathymetry. The "wave setup" effects are important to storm surge simulation and should be included in the manuscript.

Response: Thanks for your suggestion. I agree with your opinion that the "wave setup" is a very important factor in storm surge simulation. "wave setup" is a phenomenon that wave breaking in nearshore cause the water level rising. In the study area of Pingyang County, the elevation of the underwater terrain at the front of the seawall is between -0.2 to -0.6m, and the slope of the front beach is slow about 1/500 to 1/1000. In the storm surge and wave simulation of typhoon intensity with 915hpa, the water depth at the front of the seawall is about 8.0~8.20m, and the corresponding effective wave height is about 4.3~4.5m, which indicate that the waves in nearshore will not be broken. In other typhoon scenarios, the waves are basically not broken. Even if some large waves break before the embankment, preliminary analysis shows that the wave setup is about 0.1~0.5m, which is less than 10% of the maximum storm surge and is still a small amount. Therefore, "wave setup" effects was not included in this study. Thanks very much for the valuable comments made by the reviewers. We will consider the impact of wave setup in the further study.

2. The authors concluded that the scenario with the most intense typhoon (915 hPa) had the most adverse track, however, many previous studies indicated that the "size" of the hurricane (typhoon) is the main factor for storm surge height and coastal inundation extent.

Response: Thanks for your comments. For a single storm surge event, I agree that the "size" of the typhoon is an important factor for storm surge height and coastal inundation extent. The coastal inundation caused by typhoon-induced storm surge is associated with typhoon parameters including track, intensity and typhoon size. In this study, radius of maximum wind speed which is the radius from the typhoon's center to the position where the maximum wind speed occurs was used to indicate the "size" of the typhoon, and the central pressure was used to indicate the typhoon intensity. The typhoon track was set based on the analysis of historical typhoon events who caused the most serious storm surge in Pingyang County. From the perspective of typhoon intensity, this paper use an empirical relationship between this two factors as shown in Section 4.3 to calculate the value of $Rmax$. Thus the typhoon intensity and size was set to perform the storm surge simulation in Pingyang County.

3. Additionally, the typhoon size is inversely proportional to the typhoon intensity if the Jelesnianski typhoon model was used. This phenomenon should be discussed in the manuscript.

Response: Thanks for your suggestion. The typhoon size has a strong connection to the typhoon intensity. As described above, radius of maximum wind speed was used to indicate the "size" of the typhoon. Collecting the historical radius of maximum wind speed data measured in the northwest

Pacific hurricane records (2001-2018) from the Joint Typhoon Warning Center (Joint Typhoon Warning Center, 2018), it can be seen that the radius of maximum wind speed is inversely proportional to the central pressure difference.

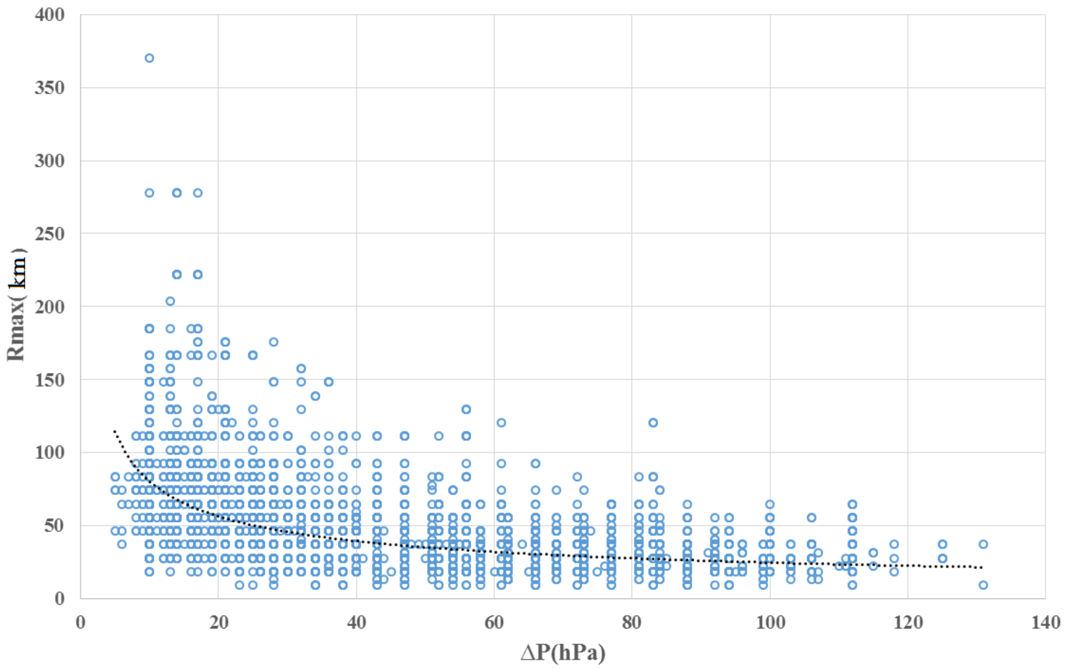


Fig 1 The relation between the central pressure difference (ΔP) and the radius of maximum wind ($Rmax$)

In this study, the empirical relationship below was used to calculate the value of $Rmax$:

$$\mathrm{R} = \mathrm{R_0} - 0.4(P_0 - 900) + 0.01(P_0 - 900)^2$$

where P_0 is the central air pressure (hPa), R is the radius of maximum wind speed, and $\mathrm{R_0}$ is an empirical constant. The recommended value is 40. The $Rmax$ and typhoon intensity also presents a negative correlation in this formula.

4. Many previous studies revealed that using a combination of parametric typhoon model and reanalysis wind produce is more suitable for storm surge and storm wave modeling. I supposed this method is also adequate for assessing the coastal inundation.

Response: Thanks for your comments. Accurate wind forcing is an important prerequisite of storm-surge and inundation simulations.A combination of parametric typhoon model and reanalysis wind produce is more suitable for storm surge and storm wave modeling for a large scale area, parametric typhoon model is used to drive the storm surge numerical model in the area influenced by typhoon, and reanalysis wind produce is need outside of typhoon.

In this study, the track of Typhoon Saomai was selected as the designed typhoon track. The designed typhoon track was translated to a position in the middle of Pingyang County and then translated to the sides by a distance of 0.25 times the radius of maximum wind speed, until the track combination that maximized the storm surge in each coastal area of Pingyang County was determined. Pingyang County is completely located within the areas of the radius of maximum wind speed, and seriously affected by typhoon. the parametric typhoon model is enough to drive the storm surge model, and the validated results show that both the water level and storm surge obtained from the storm surge simulation are highly consistent with the actual measurements.

Responses to Short Comment #1

This study proposed a deterministic method for storm surge inundation simulation under different typhoon intensity scenarios using a numerical model. Several key parameters of typhoon activities (e.g., typhoon track, radius of maximum wind speed) as well as astronomical tide and upstream flood runoff were considered to represent the compound effect of different processes during typhoon-induced storm surge. The proposed method could provide reference for the establishment of a technical system for the assessment and zonation of storm surge risk in the coastal counties of China. Following are some suggestions for the authors which might be helpful to improve the study:

Response: Thanks for your comments. We really greatly appreciate your kind help in the reviewing the manuscript. A detailed point-by-point response was presented as below according to your comments.

1. What kind of data were used in this study? and the data source?

Response: Thanks for your question. Multisource data (Table 1) were collected to perform a storm surge numerical modelling in Pingyang county. The numerical model was used to simulate the storm surge inundated range and water depth. The digital elevation map (DEM) of Pingyang county and nearshore submarine topography data were collected to construct the numerical model, and tidal observational data were used to validate the model. Historical typhoon records, including time, location, and intensity, were collected to set the typhoon parameters driving the storm surge numerical model. A field survey was carried out by Zhejiang Institute of Hydraulics and Estuary to investigate the inundation situation along the Aojiang river in Pingyang County. Researchers equipped with GPS-RTK (Global Positioning Systems, Real-Time Kinematic, which supports cm-accuracy three-dimensional positioning) and rangefinders worked in two groups to make measurements from Oct.2nd to Oct.7th in 2013. The extent of the inundation was estimated based on flooding marks, such as the accumulation of trash, signs of mud, and withered plants. In addition, the range of inundation was established through interviews with local residents.

Table 1 Multisource data used to perform storm surge numerical modelling in Pingyang County

Data type	Time series	Description	Source
Historical typhoon records	1949–2018	Time, location, and intensity of each typhoon track point	Shanghai Typhoon Institute, China Meteorological Administration
Digital elevation map and submarine topography	2015	Digital elevation map of Pingyang County and offshore submarine topography	Surveying and Mapping Bureau of Zhejiang Province
Tidal observational data	1990–2015	Hourly observational data of surge and water level for tidal station during typhoon periods	East China Sea Marine Forecasting Center, Oceanic Administration of China
Historical inundation ranges	2013	Inundation ranges caused by Fitow along the Aojiang river in Pingyang County	Field surveying by Zhejiang Institute of Hydraulics and Estuary

2. It would be better for the understanding the methodology if a technique flow chart could be provided.

Response: Thanks for your suggestion. This study proposed a framework for simulation of storm surge inundation under different typhoon intensity scenarios as shown in Fig 1.

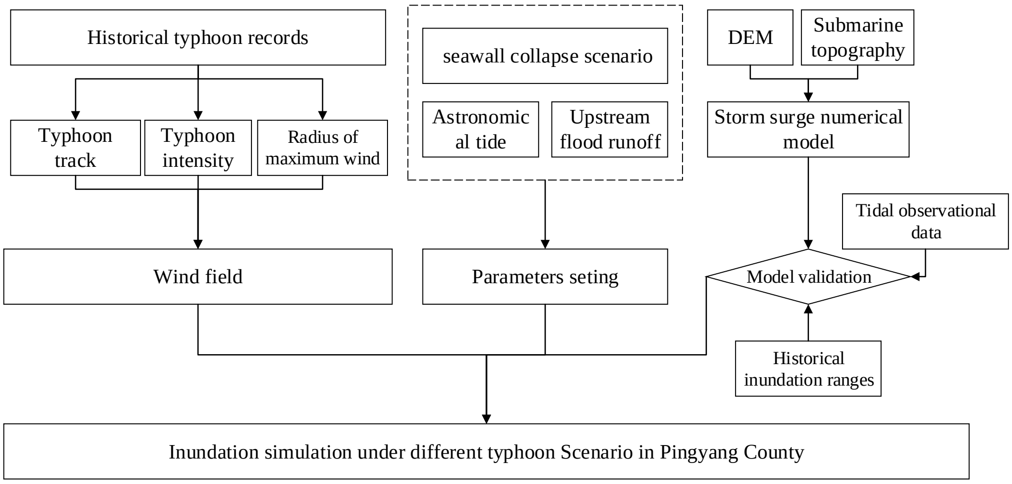


Fig 1 Framework of inundation simulation under different typhoon scenario in Pingyang County

3. It would be better if river networks and DEM could be added in the map of study area.

Response: Thanks for your suggestion. The river networks and DEM has been added in the map of the study area as show in Fig 2.

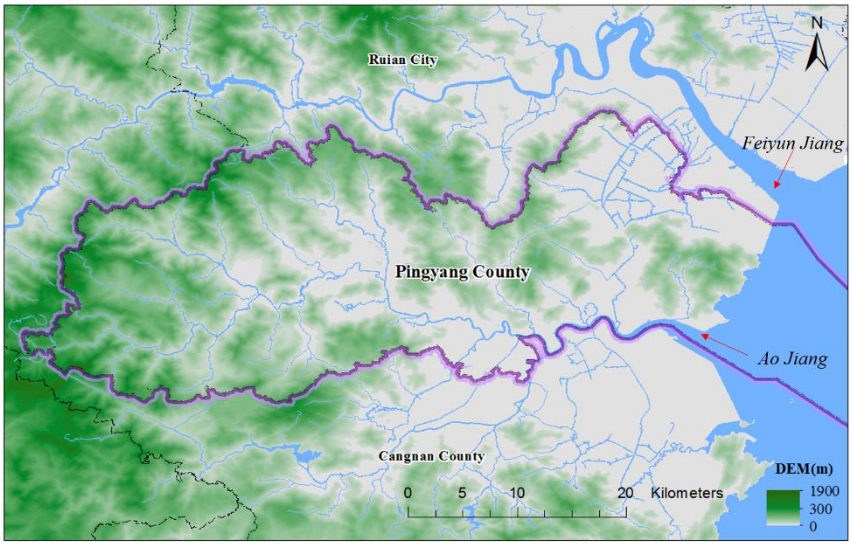
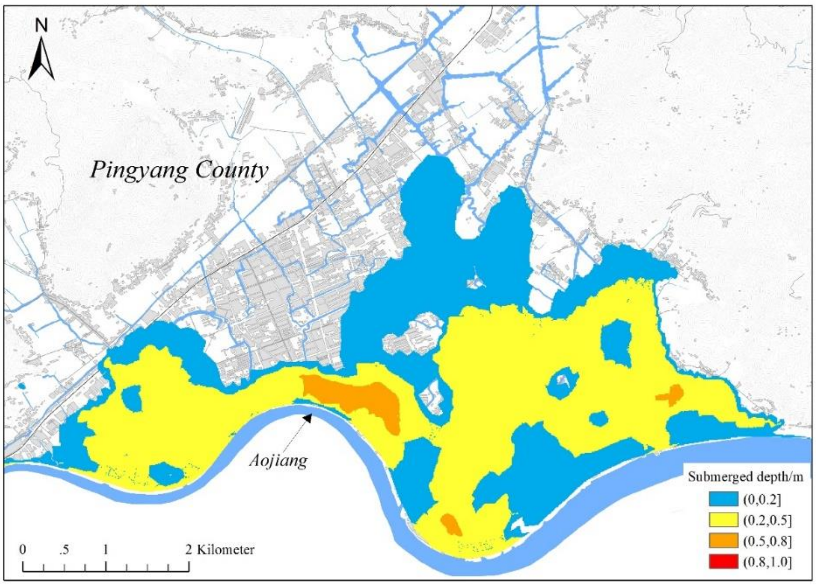


Fig 2. Case study area

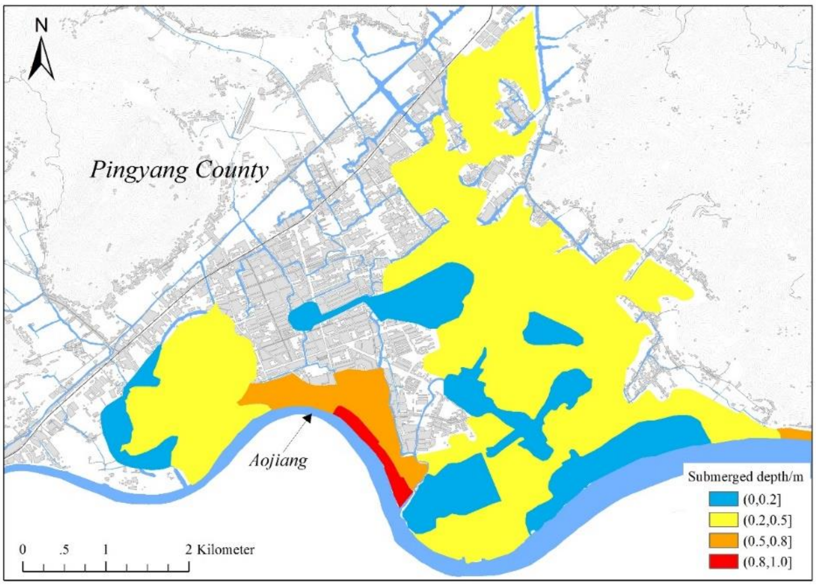
4. This study validated the numerical model in terms of the high tide level and the maximum storm surge at six tidal stations. However, a validation for the inundation simulation is absent, is it possible using historical flood records and marks?

Response: Thanks for your suggestion. A validation for the inundation simulation was performed based on the inundation ranges through field surveying. The model described in section 3 of the manuscript was used to perform a simulation of the area (see Fig 3a) along the Aojiang river (Pingyang County) inundated by Typhoon Fitow. A field survey was undertaken by the Zhejiang Institute of Hydraulics and Estuary to investigate the inundation situation in Pingyang County during the storm surge disaster period caused by Fitow(see Fig 3b). The simulated and investigated inundation areas were compared (Fig. 3). It can be seen that the surveyed and simulated inundated areas are similar. The extent of the surveyed inundated area was slightly larger than that simulated because typhoon precipitation during the period of influence of Fitow caused urban waterlogging in parts of Pingyang

County.



(a)



(b)

Fig. 3 (a) Simulated inundated area and (b) surveyed inundated area

5. The advantage of the proposed method should be further discussed.

Response: Thanks for your suggestion. We have discussed the advantage of the proposed method in the revised manuscript:

This study contributed to the methodology of storm surge inundation simulation caused by different intensities of typhoon. A high-precision numerical model for simulating storm surges was established and validated by observational data and field-surveying inundated areas after. Using these key parameters including typhoon tracks, radius of maximum wind speed, astronomical tide, and upstream flood runoff as driving factors, the inundation extents and depths in Pingyang County corresponding to the storm surges under different typhoon intensity scenarios were simulated in combination with the *storm surge numerical model. The obtained results could serve as a basis for developing a methodology for storm surge disaster risk assessment in coastal areas. The study provides an insight into the spatial distribution of the areas potentially endangered by the typhoon related flooding. It can be helpful for further hazard and risk assessments for urban planning, emergency procedures and insurance.*

Responses to Short Comment #2

The paper is overall poorly written with no scientific findings. The methods do not appear to be novel and are not sufficiently well described. It looks like a hasty paperwork without proper content in both language and techniques. No robust theory, validation, bathymetry, or topography was shown. The way of deploying local grids and river/land boundaries is probably incorrect leading to odd simulation results. Quantitative analysis is quite missing. The manuscript fails to situate the current study and results in the context of the wider literature. The presented work is not scientifically adequate for the level of an EGU journal.

Response: Thanks very much for your comments. We really greatly appreciate your kind help in the reviewing the manuscript. We substantially revised the paper based on your comments.

(1) The author team has been carefully checked the manuscript again, and some minor errors was modified in the revised manuscript. The revised manuscript has been reorganized according to two short comments and two reference report. At the same time, we asked one language professional and Editage to improve the language issues of the revised manuscript.

(2) This paper presents a method to analyze typhoon-induced storm surge under different typhoon intensities from the perspective of typhoon parameters, astronomical tide and upstream flood runoff. The proposed method was composed by four parts: model configuration, model validation, parameters setting and inundation simulation. Based on the historical observational data, the key parameters (e.g., typhoon track, radius of maximum wind speed, astronomical tide, and upstream flood runoff) could be set to drive the storm surge numerical model. The obtained results could serve as a basis for developing a methodology aimed at storm surge disaster risk assessment in coastal areas. The proposed method could be easily adopted in various coastal areas and serves as an effective tool for the decision making in storm surge disaster risk reduction practices.

(3) In the revised manuscript, the methods would be reorganized as a single section to be presented, and a technical framework will be proposed for simulation of storm surge inundation under different typhoon intensity scenarios as shown in Fig 1 with a detailed description.

(4) Fig 1 and Fig 2 were redrawn according to your advice, and the bathymetry and topography was added in the Figures. Detailed information could be found in the Response to Referent Report 1.

(5) The quantitative analysis could be found in the Section of Calculation results, and more detailed information would be presented in the revised manuscript.

Again, it will be our great honor to receive more helpful comments to improve the manuscript.

Simulation of storm surge inundation under different typhoon intensity scenarios: Case study of Pingyang County, China

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Abstract: China is one of the countries that are most seriously affected by storm surges. In recent years, storm surges in coastal areas of China have caused huge economic losses and a large number of human casualties. Knowledge of the inundation range and water depth of storm surges under different typhoon intensities could assist pre-disaster risk assessment and making evacuation plans, as well as provide decision support for responding to storm surges. This study contributed to the methodology of storm surge inundation simulation caused by different typhoon intensities which was composed by four parts: model configuration, model validation, parameters setting and inundation simulation. Taking Pingyang County in Zhejiang Province as a case study area, ~~Based on historical typhoon-induced storm surges in the study area of Pingyang County in Zhejiang Province, China, key~~ parameters including typhoon tracks, radius of maximum wind speed, astronomical tide, and upstream flood runoff were determined for different typhoon intensities. Numerical simulations were conducted using these parameters to investigate the inundation range and water depth distribution of storm surges in Pingyang County under five different intensity scenarios (915, 925, 935, 945, and 965 hPa) with consideration of the impact of seawall collapse, and ~~.~~the obtained results is consistent with the actual situation in the study area. ~~The simulation results show that the range of storm surge inundation expands with increasing typhoon intensity. The scenario with the most intense typhoon (915 hPa) had the most adverse track, with an associated area of inundation of 233 km^2 that included most areas of the town of Aojiang, eastern areas of Wanquan, northern areas of Songbu, as well as parts of Kunyang and Shuitou.~~The proposed method could be easily adopted in various coastal counties and serves as an effective tool for the decision making in storm surge disaster risk reduction practices.

Keywords: Intensity scenarios; Inundation simulation; Typhoon-induced storm surge; Pingyang County; ~~Typhoon-induced storm surge~~

1 Introduction

China is among the few countries affected seriously by storm surges. A storm surge can cause overflow of tide water and seawall destruction that can result in flooding in coastal areas, which can be extremely destructive and can have serious impact on surrounding areas (Sun et al. 2015). Storm surges have occurred along much of China's coast from south to north (Gao et al. 2014). On average, approximately nine typhoons annually make landfall over China (Shi et al. 2015), most of which cause storm surges. In 2018, storm surge disasters caused coastal flooding in China that resulted in 3 deaths and direct economic losses of RMB 4.456 billion (Ministry of Natural Resources 2019). With the recent rapid socioeconomic development in China, industrialization and urbanization processes in coastal areas have accelerated, and both the population density and the social wealth in such areas have increased sharply. Concurrently, owing to global climate change and sea level rise, the occurrence of weather situations that trigger storm surges has become more frequent and the associated risk level of coastal storm surges has increased significantly (Fang et al., 2014; Yasser et al., 2018). Fortunately, the number of fatalities in China due to storm surges has decreased significantly because of improvements in the regional early warning capability (Shi et al. 2015). Thus, the focus on storm surge disasters has changed from reduction of disaster losses to mitigation of disaster risks. Therefore, ~~increasing importance~~research on storm surge risk has been attracted more and more attention~~attached to studies on storm surge risk~~ (Shi et al., 2019). Storm surge risk assessment aims to estimate~~s~~ the risk level of ~~future~~ storm surges in a certain region based on deterministic numerical simulation in combination with designed probabilistic storm surge scenarios (Shi et al. 2013; Wang et al. 2018). The calculation of storm surge under scenarios with storms of different intensity is an important part of storm surge risk assessment. The calculation results could provide important decision-making support for the ~~planned~~ response to storm surges in coastal areas, and they could assist in both the pre-assessment of storm surge disasters and the preparation of storm surge emergency evacuation plans. Following the earthquake-induced “3.11” tsunami that occurred in Japan in 2011, scientific research on many aspects of marine disaster risk management became of great concern to various governments. With consideration of storm surge disaster as the primary hazard, China commenced a project for marine disaster risk assessment and zoning, and it subsequently released its marine industry standard, *the Technical Guidelines for Risk Assessment and Zoning of Marine Disaster Part 1: Storm Surge* (Liu et al. 2018). Calculation of the inundation range and water depth of storm surges associated with typhoons of different intensity is one of the most important tasks in storm surge risk assessment.

The core element of simulation of inundation by storm surge disaster under scenarios of different typhoon intensity is to set key parameters for both the typhoons and the storm tides (e.g., typhoon track, typhoon intensity, radius of maximum wind speed, and astronomical tide) under different conditions (Shi et al, 2020). ~~Wang (2002) calculated the maximum possible land inundation range based on the translation speed of various historical typhoons (category: 3–5) in the study area, in combination with the SLOSH numerical model. A universal product for the determination of inundation range and water depth distribution for typhoons of different intensity was developed, and it was concluded that storm surges caused by category 5 typhoons would be the probable maximum storm surge.~~ Tomohiro et al. (2010) set key parameters for the largest possible typhoon-induced storm surge in different regions of Japan by simulating typhoon track translation using indicators of the Ise Bay typhoon (the most serious typhoon event recorded in Japan’s history) as reference typhoon parameters. ~~This method is of wide applicability and it is easy to implement; however, it also has certain limitations attributable to its dependence on the availability of recorded information on historical storm surge events.~~ To overcome th~~e~~is limitation of historical records ~~problem~~, a stochastic modelling ~~complete~~ method has ~~gradually~~ been developed for ~~stochastic~~ simulation of typhoon track and intensity. ~~The main idea of such a~~This method is to analyze the statistical probability characteristics of historical typhoons in terms of their annual frequency, seasonal distribution, track distribution, intensity, and ~~range of~~ influence ~~range~~areas. Based on these features, the generation, development, and ~~extinction~~ lysis of typhoons can be simulated to generate a large number of ~~complete event~~typhoon ~~samples~~events ~~of typhoon track and intensity~~ (Powell et al., 2005; Lin et al., 2010). By selecting events with different typhoon intensity from the generated samples, the inundation ~~–range~~extents and ~~water~~ depths of the~~in a~~ study area can be calculated using the~~a~~ storm surge numerical model ~~of storm surges~~ (Wood et al. 2006; Wahl et al. 2015), and ~~.~~these researches mainly focus on the coast of North Atlantic Ocean. Considering the typhoon landing and historical storm surge events happened in the coastal areas of China, how to set the parameters for performing the simulation of typhoon-induced storm surge under different typhoon intensity scenarios is an interesting and important topic towards the coast of China.

This study considered Pingyang County of Zhejiang Province (China) as ~~the target~~a case study area. ~~.~~ The objective was to propose a ~~technical~~ deterministic method to calculate the inundation extents and depths caused by different typhoon intensity scenarios combined with the storm surge numerical model. The ~~on setting~~ key parameters (e.g., typhoon intensity, typhoon track, maximum wind speed radius~~, astronomical tide, and upstream flood runoff~~) corresponding to the characteristics of typhoons landing the coastal areas of China was set. The astronomical tide, upstream flood runoff and seawall collapse was taken into consideration as an important factor in the storm surge simulation. The results aim to contribute to the methodology of quantitative assessment of storm surge hazards for coastal counties.~~of typhoon-induced storm surge, and to calculate the inundation range and water depth distribution caused by different typhoon intensity scenarios.~~

2 Materials

2.1 Case study area

Pingyang County is a coastal county belonging to the city of Wenzhou in Zhejiang Province, China (Fig~~ure~~. 1) and is affected most frequently by storm surge in coastal areas. It is located in the tropical storm zone of the western Pacific Ocean and is generally exposed to the risk of storm surges during July–October. Pingyang County lies within the region 27°21´–27°46´N, 120°24′–121°08′E, and it is bordered by Ruian, Wencheng, Taishun, and Cangnan counties. The county extends roughly 83 km from e~~E~~ast to~~–~~ w~~W~~est and roughly 25.4 km from n~~N~~orth to ~~–~~s~~S~~outh, covering an area of approximately 1051 km2. It is a highly developed and densely populated area of China with considerable asset exposure. Pingyang County has a population of approximately 800,000, and it is the first National Coastal Economic Open County with customs, ports, and important industries. The coastal zone of Pingyang County, which extends for 22 km, is surrounded by sea on its eastern, southern, and northern sides. The Ao J~~j~~iang and Feiyun ~~rivers~~ Jiang flow across the county and they discharge into the East China Sea. Storm surges frequently hit this county, which is one of the reasons why the China State Oceanic Administration approved Pingyang County as the first National Marine Disaster Mitigation Comprehensive Demonstration Area in China.

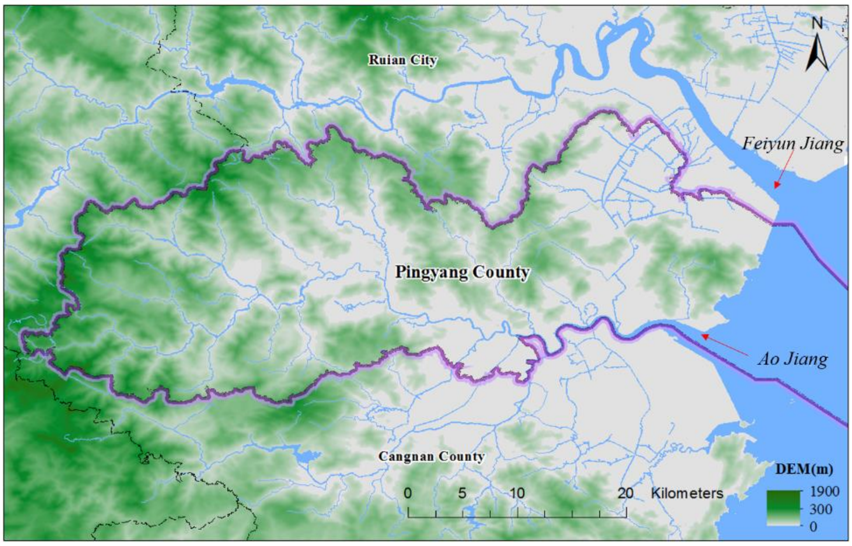


Figure. 1 Case study area

2.2 Data

Multisource data (Table 1) were collected to perform a storm surge numerical modelling in Pingyang county. The digital elevation map (DEM) of Pingyang county and nearshore submarine topography data were collected to construct the numerical model, and tidal observational data were used to validate the model. Historical typhoon records, including time, location, and intensity, were collected to set the typhoon parameters driving the storm surge numerical model. A field survey was carried out by Zhejiang Institute of Hydraulics and Estuary to investigate the inundation situation along the Ao Jiang river in Pingyang County. Researchers equipped with GPS-RTK (Global Positioning Systems, Real-Time Kinematic) and rangefinders worked in two groups to make measurements from Oct.2nd to Oct.7th in 2013. The extent of the inundation was estimated based on flooding marks, such as the accumulation of trash, signs of mud, and withered plants. In addition, the extent of inundation was established through interviews with local residents.

Table 1 Multisource data used to perform storm surge numerical modelling in Pingyang County

Data type	Time series	Description	Source
Historical typhoon records	1949–2018	Time, location, and intensity of each typhoon track point	Shanghai Typhoon Institute, China Meteorological

			Administration
Digital elevation map and submarine topography	2015	Digital elevation map of Pingyang County and offshore submarine topography	Surveying and Mapping Bureau of Zhejiang Province
Tidal observational data	1990–2015	Hourly observational data of surge and water level for tidal station during typhoon periods	East China Sea Marine Forecasting Center, Oceanic Administration of China
Historical inundation ranges	2013	Inundation ranges caused by Fitow along the Aojiang river in Pingyang County	Field surveying by Zhejiang Institute of Hydraulics and Estuary

3 Methods

This study proposed a framework for calculation of storm surge inundation simulation under different typhoon intensity scenarios (Fig.2). The proposed framework was composed by four parts: model configuration, model validation, parameters setting and inundation simulation. The numerical model was used to simulate the storm surge inundated range and water depth, and the DEM and nearshore submarine topography data was used to construct the storm surge numerical model. The numerical model was validated by historical observational data of tidal station and field-surveying data of inundated areas. Based on the historical observational data, the key parameters (e.g., typhoon track, radius of maximum wind speed, astronomical tide, and upstream flood runoff) could be set to drive the storm surge numerical model. The proposed method could be easily adopted in various coastal counties and serves as an effective tool for the decision making in storm surge disaster risk reduction practices.

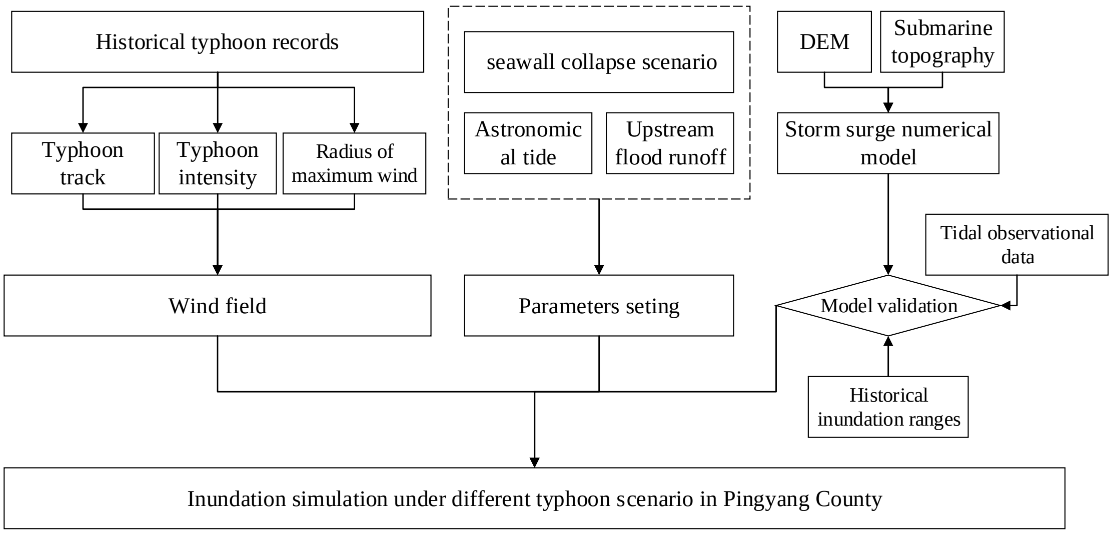


Fig. 2 Framework of storm surge inundation simulation under diffirent typhoon scenario in Pingyang County

~~3 Establishment of the storm surge numerical model~~

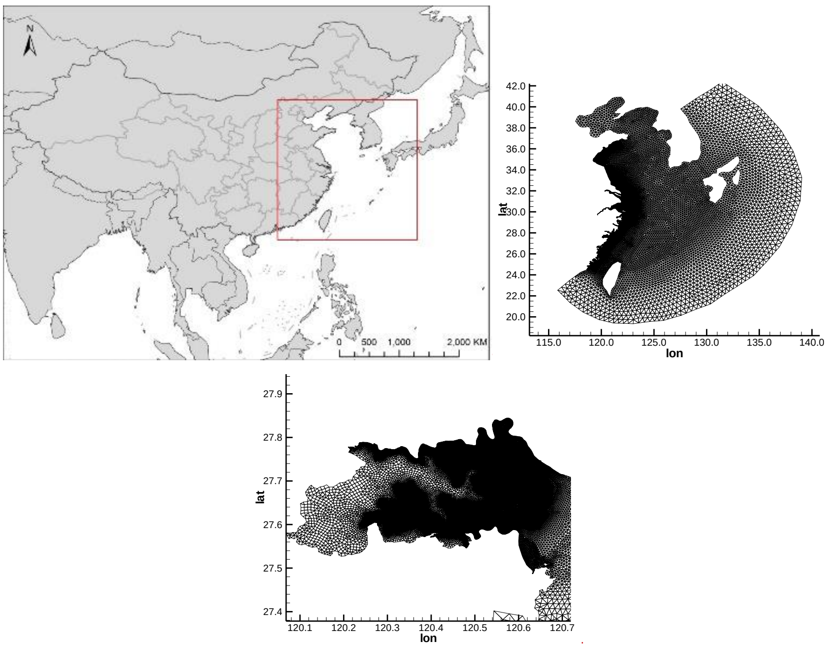
3.1 Model configuration

The typhoon-astronomical-flood-wave coupled numerical model ~~The storm surge numerical model~~ used in this study, developed by the Zhejiang Institute of Hydraulics and Estuary, is based on the unstructured-grid finite volume method, and more detailed model information could be found in Chen et al (2019). It has characteristics of high efficiency, accuracy, conservation, and automatic capture of intermittent flow. This model could be used to simulate conventional river channel flow and offshore water flow including flood evolution, astronomical tides, storm surges, and flooding. The storm surge simulations were performed in combination with the calculation of river runoff and consideration of typhoon wind and air pressure fields. Thus, the model was capable of simulating large-scale detailed storm surge flooding. The open-sea boundary of the model was set near the first typhoon warning line in China's offshore area (Fig. 3a). The model contained triangular and quadrilateral grids consisting of 258,543 units and 173,910 nodes. The coverage extended to Bohai Bay and the Sea of Japan in the north, to the south of Taiwan in the south, and to the east of the Ryukyu Islands (as shown in Figure. 32aa) in the east. The upper boundary of the Aojiang River was set at Daitou, the upper boundary of the Feiyun River was at Zhaoshandu, and the upper boundary of the Oujiang River was set at Weiren. The grid for the offshore area and land in Pingyang County with elevation of <30 m (including Nanji Island) had a side length of 50–200 m, and the minimum side length was 15 m (as shown in Figure. 32bb). The model covered the Bohai Sea, Yellow Sea, East China Sea, Sea of Japan, Korean Strait, Taiwan Strait, Yangtze River Estuary, Hangzhou Bay, and Qiantang River. The mesh grid was finest in localized areas of the Zhejiang offshore region, Oujiang River Estuary, Feiyun River Estuary, and Aojiang River Estuary.

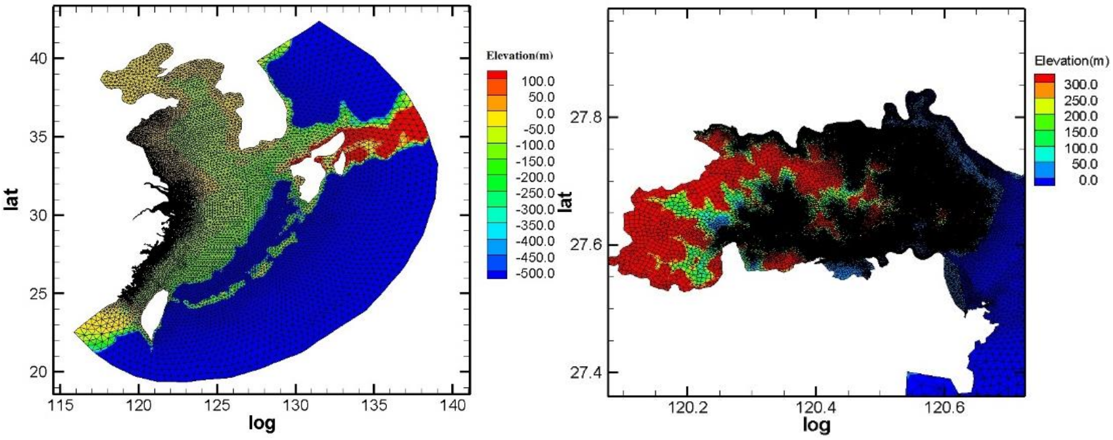
Waves caused by typhoon are simulated by Simulating Waves Nearshore (SWAN) model in this study (Booij et al, 1999). The SWAN model is a third-generation numerical wave model, which is used to simulate wind-generated wave propagation in coastal regions. It can describe the evolution of wave fields under specific wind, flow and underwater terrain conditions in shallow waters. The governing equation is as follows.

$$\frac{\partial}{\partial_t}N + \frac{\partial}{\partial_x}C_xN + \frac{\partial}{\partial_y}C_yN + \frac{\partial}{\partial_\sigma}C_\sigma N + \frac{\partial}{\partial_\theta}C_\theta N = \frac{S}{\sigma} \quad (1)$$

In the equation, N is wave action, σ is relative frequency of waves, θ is wave direction, and S is source item. C_x and C_y are wave propagation speed in x and y direction, respectively. C_σ is propagation speed of wave action in frequency space, and C_θ is the propagation speed of wave action in wave direction space. Based on the wave elements and the structural parameters of the seawall, the overtopping discharge is calculated by the empirical formula. In the simulation of dike-breaching, the varying dike top elevation is applied according to overtopping discharge to simulate the process of dike-breaching.



(a) (b) (c)



(b) (c)

Figure. 32 (a) Model domain with unstructured triangular grids (in red box), (ab) mesh computational domain of the numerical model in the offshore area, and (bc) refined mesh in Pingyang County

3.2 External force

The storm surge numerical model was driven by wind stress and the atmospheric pressure gradient acting on the surface. The Jelesnianski model was chosen to generate the wind and pressure fields (Jelesnianski, 1965), for which the calculation formulas are as followss:

$$W = \begin{cases} \frac{r}{r+R}\left(V_{0x}\vec{\imath} + V_{0y}\vec{\jmath}\right) + W_R\left(\frac{r}{R}\right)^{\frac{3}{2}} \frac{(A\vec{\imath}+B\vec{\jmath})}{r}, \quad (0<r\leq R) \\ \frac{R}{r+R}\left(V_{0x}\vec{\imath} + V_{0y}\vec{\jmath}\right) + W_R\left(\frac{R}{r}\right)^{\beta} \frac{(A\vec{\imath}+B\vec{\jmath})}{r}, \quad (r>R) \end{cases}$$

(12)

$$P_a = \begin{cases} P_0 + \frac{1}{4}(P_\infty - P_0)\left(\frac{r}{R}\right)^3, \quad (0<r\leq R) \\ P_\infty - \frac{3}{4}(P_\infty - P_0)\frac{R}{r}, \quad (r>R) \end{cases}$$

(23)

and

$$A = -[(x-x_c)\sin\theta + (y-y_c)\cos\theta]$$

(34)

$$B = (x-x_c)\cos\theta + (y-y_c)\sin\theta$$

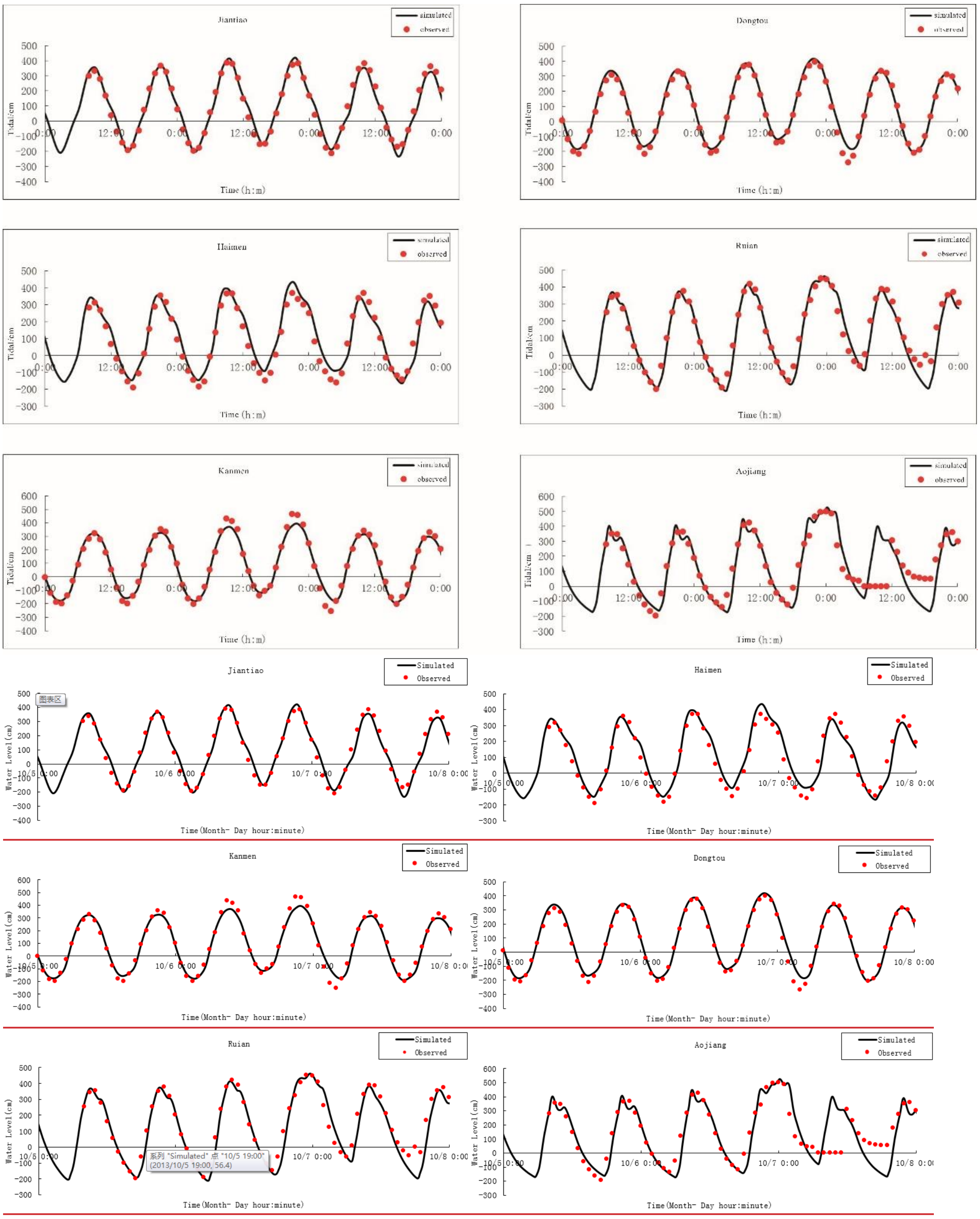
(45)

In the above equations, R is the radius of maximum wind speed, r is the distance from the calculated point to the center of the typhoon, (V_{0x}, V_{0y}) is the translation speed of the typhoon, (x, y) and (x_c, y_c) are the coordinates of the calculated point and the typhoon center, respectively, θ is the inflow angle, P_0 is the central pressure of the typhoon, P_∞ is the atmospheric pressure at infinite distance, and W_R is the maximum wind speed of the typhoon.

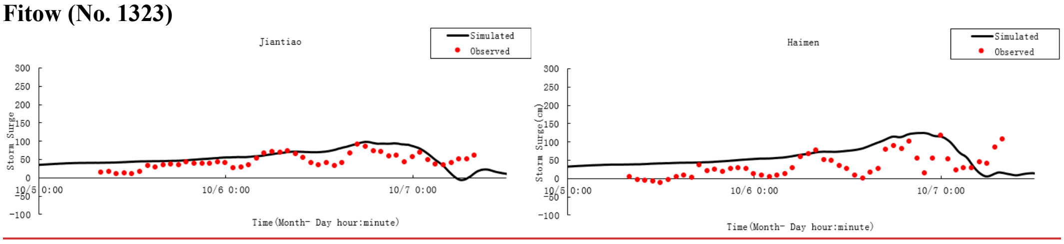
3.3 Model verification

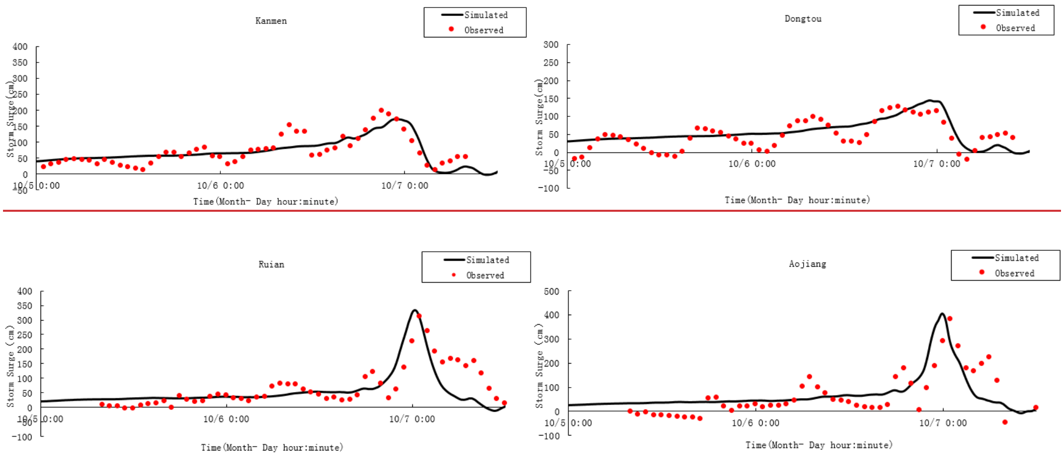
Verification of the storm surge numerical model was performed using 20 typhoon-induced storm surge events that affected Pingyang County during 1990 to –2015. The tidal range along Pingyang coast is about 4.45m. The differences betweenError statistics between each of the 20 the simulated and observed water level and surge of the 20 typhoon-induced storm surge processes events were compiled in terms of the high tide level (Table 1) and the maximum storm surge (Table 2) at six tidal stations (Jiantiao, Haimen, Kanmen, Dongtou, Ruian, and Minjiang as shown in Fig.4)) close to Pingyang County as shown in Table 2 and 3. According to the statistical results, the average error of the high tide level was 14 cm, and 94% of the highest tide level errors were <30 cm. TThe absolute average error of the high tidewater level of all involved tidal stations was 12–18 cm, and the average error of the storm surge high tide level of all involved typhoons was 8–25 cm. The average error of the maximum storm surge was 13 cm, and 55% of the maximum storm surge errors were <10 cm or 10% of the maximum storm surge. The absolute average maximum storm surge error of all involved tidal stations was 11–15 cm, and the average error of the maximum storm surge of all involved typhoons was 7–20 cm. Storm surge caused by typhoon Fitow (No. 1323) is the most serious event that affected Pingyang County in the past ten years. Verification of the high tidewater level and of the storm surge for of 6 tidal stations affected by tTyphoon Fitow (No. 1323) is presented in Figure. 53 and 64, respectively. It can be seen that both the phase and the high tidewater level obtained from the storm surge simulation are highly consistent with the actual measurements, proving that the storm surge numerical model developed in this study was reliable.

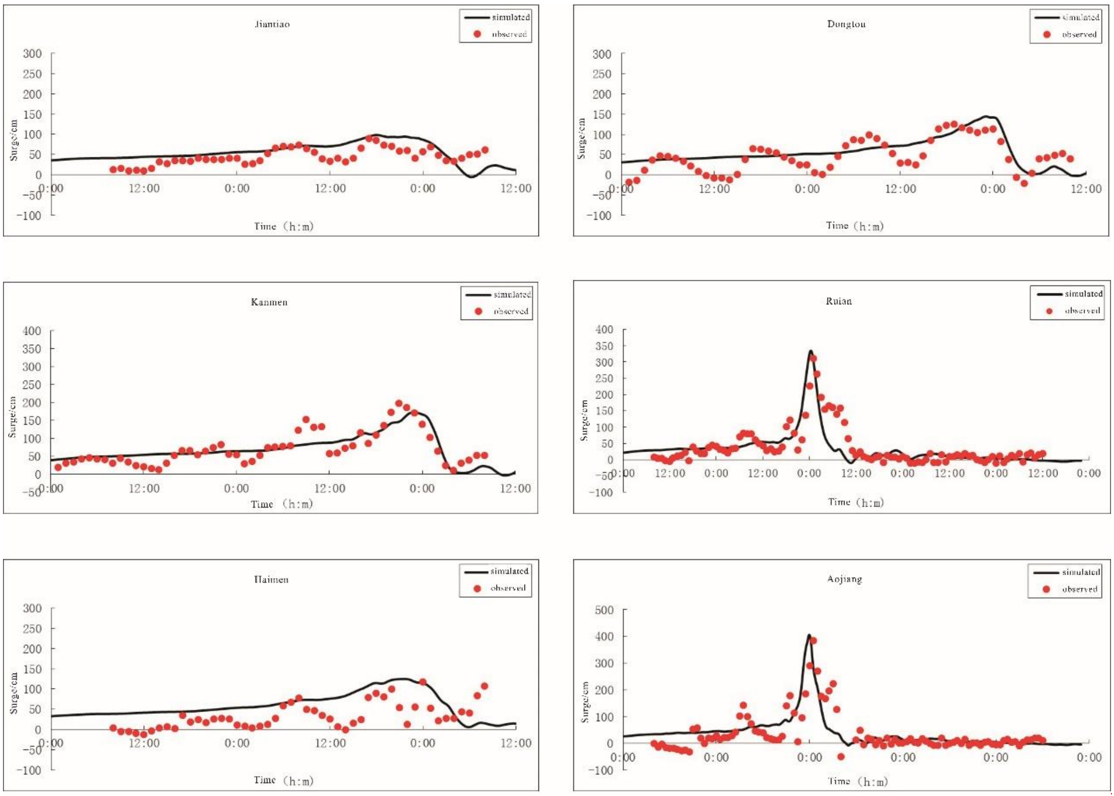
Fig.4 the distribution of tidal station along the coastal Zhejing Province



Fig~~ure~~. 5~~3~~ Verification of the high tide level for tidal stations affected by the storm surge caused by Typhoon Fitow (No. 1323)







Fig~~ure~~. 6~~4~~ Verification of the storm surge for tidal stations affected by the storm surge caused by Typhoon Fitow (No. 1323)

Table 2~~1~~ Error statistics in terms of maximum ~~the high tide~~water level during landfall of 20 typical typhoons (unit: cm)

	Jiantiao	Haimen	Kanmen	Dongtou	Ruian	Aojiang	Average
9015	——	——	3	2	-23	——	9~~8~~
9216	-6	-24	——	-15	-1	4	10~~2~~
9219	20	23	-1	18	-7	-3	12~~1~~
9417	14	4	——	31	11	-3	11
9608	-19	-20	——	-30	-25	2	19~~8~~
9711	-17	11	-24	——	-24	-31	22~~0~~

0004	16	25	-20	1	14	15	153
0008	12	-1	-26	12	7	13	121
0108	18	14	16	17	24	22	198
0216	5	-16	-11	17	21	17	15
0505	31	-5	-31	-33	-15	31	241
0509	-17	-17	-14	-14	2	7	123
0515	0	28	-17	-4	1	6	911
0604	-2	-14	-24	-9	-17	-1	114
0608	1	-13	-2	3	15	23	109
0713	16	4	10	-1	25	26	145
0716	19	8	14	13	21	15	15
0908	20	22	———	———	10	2	142
1209	6	-10	-21	-10	16	15	13
1323	26	31	-55	19	-8	-17	265
Average	14	15	18	14	14	134	154.8

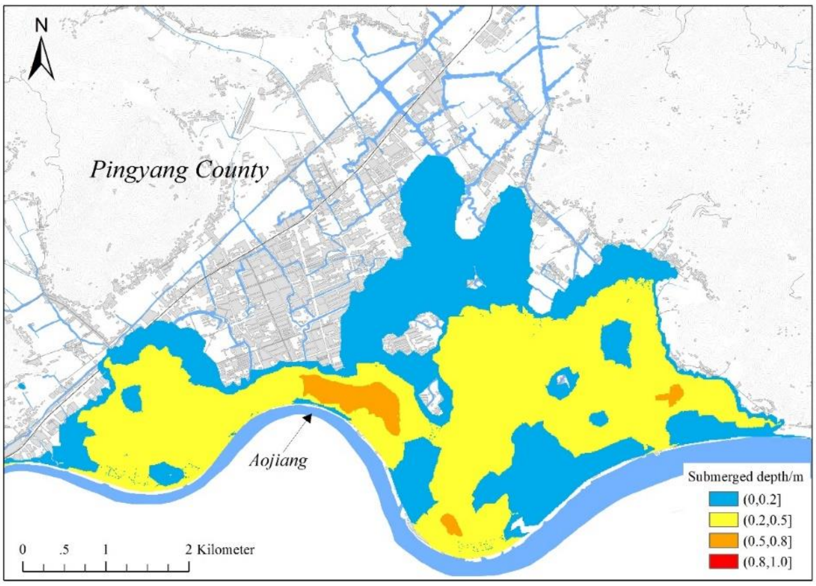
Note: “———”means no observational value.

Table 32 Error statistics in terms of the maximum storm surge during landfall of 20 typical typhoons (unit: cm)

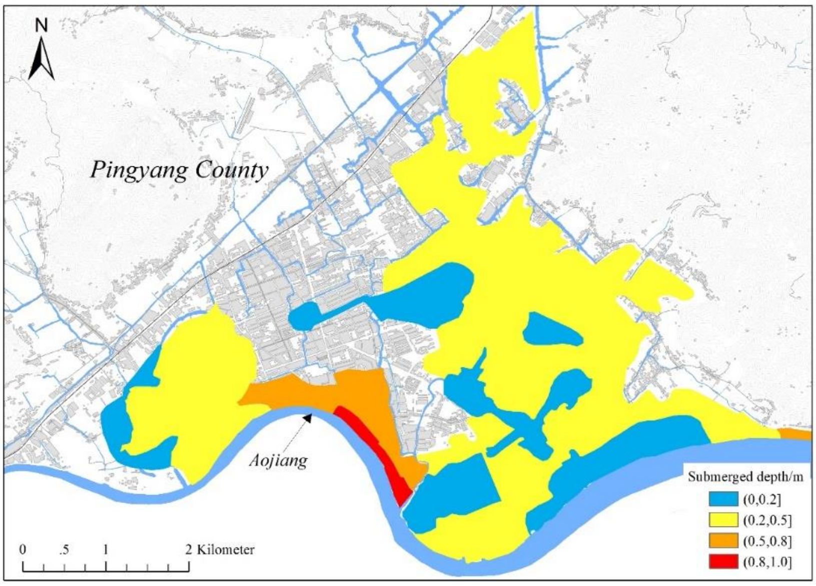
	Jiantiao	Haimen	Kanmen	Dongtou	Ruian	Aojiang	Average
9015	———	———	-11	-17	-9	———	121
9216	-8	-6	-34	-6	-2	-12	11
9219	6	15	-11	14	13	20	13
9417	-21	-17	-2	———	-20	-8	142
9608	-10	-21	-35	-10	-16	-10	175
9711	23	21	-15	-20	-1	-7	157
0004	10	12	-14	7	10	-4	108
0008	3	-2	-2	16	-2	10	67
0108	10	10	1	27	5	3	9
0216	11	2	2	2	26	19	101
0505	-15	-5	-26	-10	-26	-38	20
0509	-8	17	-14	8	-15	-10	121
0515	9	12	-20	-12	-23	-10	142
0604	-10	-21	-35	10	15	9	176
0608	-1	5	10	-13	13	-3	8
0713	21	-2	-8	28	17	18	16
0716	9	15	20	2	17	21	145
0908	-42	-3	———	———	-6	-5	141
1209	———	———	-6	———	10	13	10
1323	5	7	-27	12	21	19	157
Average	12	11	15	13	13	13	13

Note: “———”means———” means no observational value.

Besides, a validation for the inundation simulation was performed based on the inundation ranges through field surveying. The model described above was used to perform a simulation of the area along the Aojiang river (Pingyang County) inundated by Typhoon Fitow. A field survey was undertaken by the Zhejiang Institute of Hydraulics and Estuary to investigate the inundation areas in Pingyang County during the storm surge disaster period caused by Fitow (Fig. 7b). The simulated and investigated inundation areas were compared (Fig. 7). It can be seen that the surveyed and simulated inundated areas are similar. The extent of the surveyed inundated area was slightly larger than that simulated because typhoon precipitation during the period of influence of Fitow caused urban waterlogging in parts of Pingyang County.



(a)



(b)

Fig. 7 (a) Simulated inundated area and (b) surveyed inundated area

3.4 ~~4~~ Parameter setting

~~4.1~~3.4.1 ~~(1)~~ Typhoon intensity

Pingyang County is frequently affected by typhoons, and is~~. During 1951–2013, the county~~ experienced 132 hazardous typhoons~~–~~ during 1951-2013 with an average ~~occurrence frequency~~ of 2.13 times per year. ~~Since 1990, t~~The county has been affected by 20 typhoons with central air pressure in the range of 920–985 hPa (average: 965 hPa) since 1990. Based on the actual needs for response to coastal storm surges, this study considered typhoons with five different levels of intensity (Table ~~3~~4), which were based on the central air pressure during landfall with reference to *the Technical Guidelines for Risk Assessment and Zoning of Marine Disaster Part 1: Storm Surge* (Liu et al. 2018).

Table ~~3~~4 Typhoon intensity scenarios

Typhoon Intensity	I	II	III	IV	V
Maximum wind force	Level 12-13	Level 14-15	Level 16	Level 17	Above 17
Minimum air central pressure (hPa)	965	945	935	925	915

3.4.2 ~~(2)~~ Typhoon track

This study selected the two typhoons that had the most severe impact on Pingyang County and that generated the most significant storm surge in history, i.e., Typhoon Fred (No. 9417) and Typhoon Saomai (No. 0608) as shown in Fig 8. Typhoon Fred caused the most severe storm surge in central and southern parts of Zhejiang Province (including Pingyang County) since 1949. The minimum central air pressure of this typhoon was 935 hPa; however, when making landfall near Ruian, the central air pressure was 960 hPa and the radius of maximum wind speed was approximately 50 km. This typhoon landed at the time of the highest astronomical tide and it generated the highest ~~tide~~ water level ever recorded in the coastal area, causing the water level at Ao Jiang Station up to 6.56m. Typhoon Saomai had the lowest central air pressure and the fastest wind speed of any typhoon since 1949. The minimum central air pressure reached 915 hPa; however, when making landfall near the Cangnan tidal station, the central air pressure was 920 hPa and the radius of maximum wind speed was approximately 15 km. Before making landfall, both typhoons traveled in a direction perpendicular to the shoreline, conducive to generating the greatest storm surge.

To determine which of these two typhoons had the track that caused the larger storm surge in Pingyang County under the same conditions, both were assumed to have central air pressure of 915 hPa, radius of maximum wind speed of 36 km, and constant direction of movement. The track of Typhoon Fred was translated to the landing site of Typhoon Saomai. The results showed that the maximum storm surge of Typhoon Fred and Typhoon Saomai was 7.22 and 7.47 m, respectively, at Aojiang and 7.00 and 7.03 m, respectively, at Ruian. As the storm surge associated with Typhoon Saomai was slightly larger, the track of this typhoon was selected as the designed typhoon track. The designed typhoon track was translated to a position in the middle of Pingyang County and then translated to the sides by a distance of 0.25 times the radius of maximum wind speed, until the track combination that maximized the storm surge in each coastal area of Pingyang County was determined (Fig.9). This track was then used for the inundation superposition calculation.

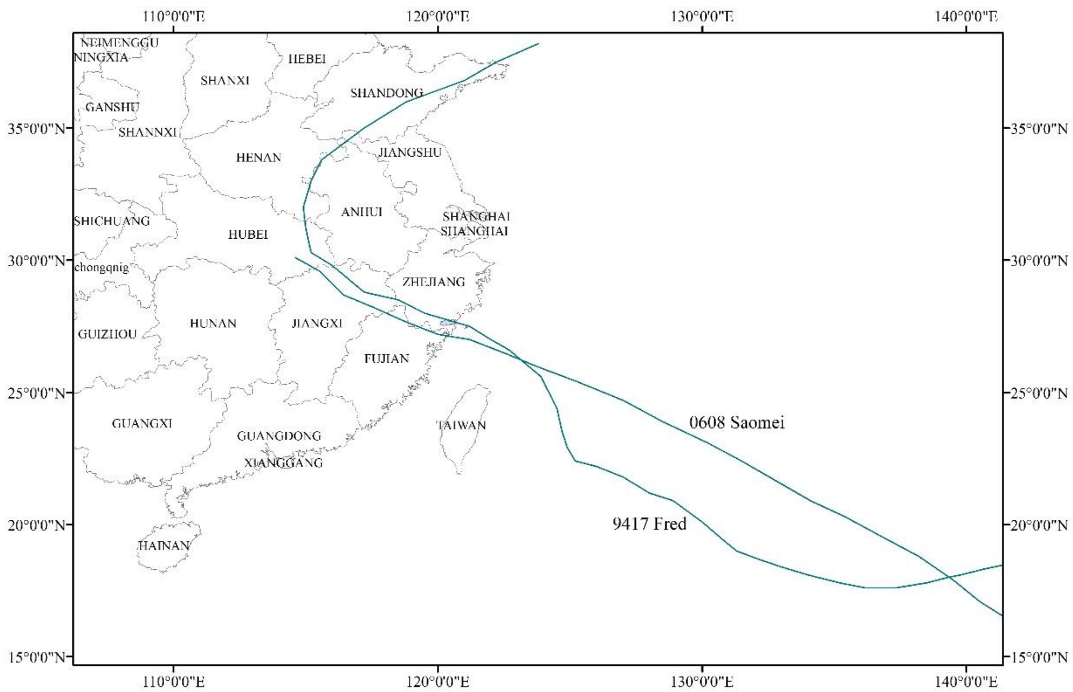


Fig 8 Typhoon track of 9417 "Fred" and 0608"Saomei"

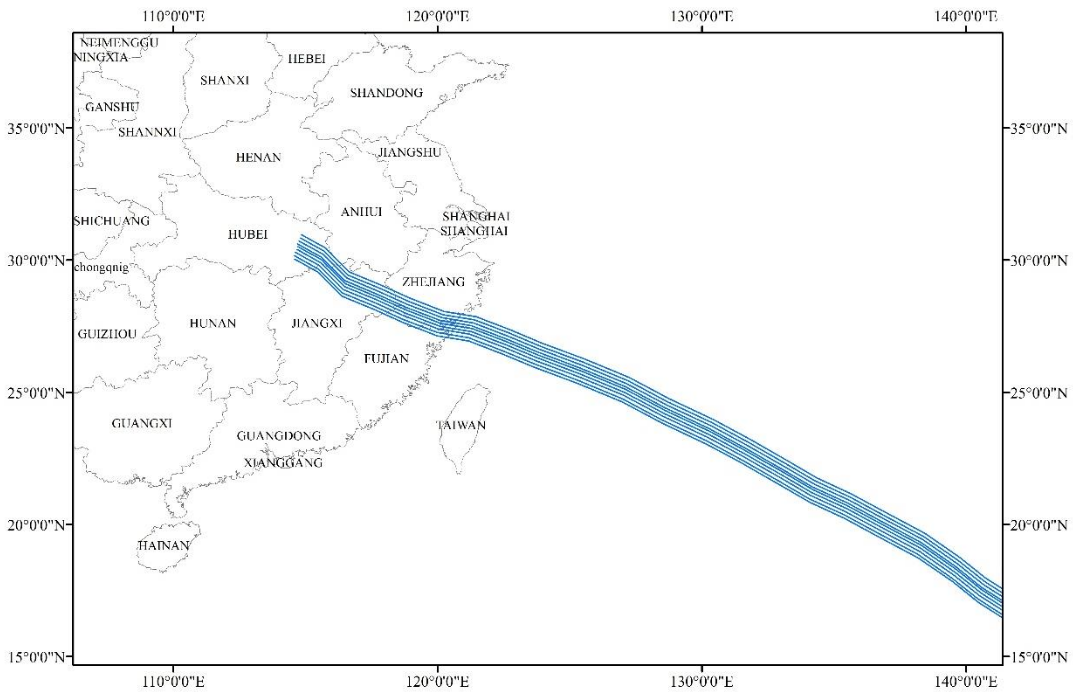


Fig. 9 "designed typhoon" track set over Pingyang County

3.4.3~~(3)~~ Radius of maximum wind speed

The radius of maximum wind speed which is the radius from the typhoon's center to the position where the maximum wind speed occurs was used to indicate the "size" of the typhoon. The radius of maximum wind speed of a typhoon is an important factor for the simulating of storm surge height and coastal inundation extent.~~affecting the magnitude of storm surge.~~ Collecting the historical radius of maximum wind speed data measured in the northwest Pacific hurricane records (2001-2018) from the Joint Typhoon Warning Center (Joint Typhoon Warning Center,2018), it can be seen that the radius of maximum wind speed is inversely proportional to the central pressure difference (Fig 10). The radius of maximum wind speed has a strong relationship with the typhoon intensity, and an empirical formula was used to ~~of the typhoons selected in this study was~~ calculate the radius of maximum wind speedd ~~using the following empirical relationship~~as below:

$$R = R_0 - 0.4(P_0 - 900) + 0.01(P_0 - 900)^2 \qquad (~~5~~6)$$

where P_0 is the central air pressure (hPa), R is the radius of maximum wind speed, and R_0 is an empirical constant. The recommended value is 40, although this can also be adjusted by the fitting accuracy of the air pressure or the wind speed. Thus, the radius of maximum wind speed can be calculated from the central air pressure of the typhoons with five different intensities at the time of landfall, i.e., 56, 42, 38, 36, and 36 km.

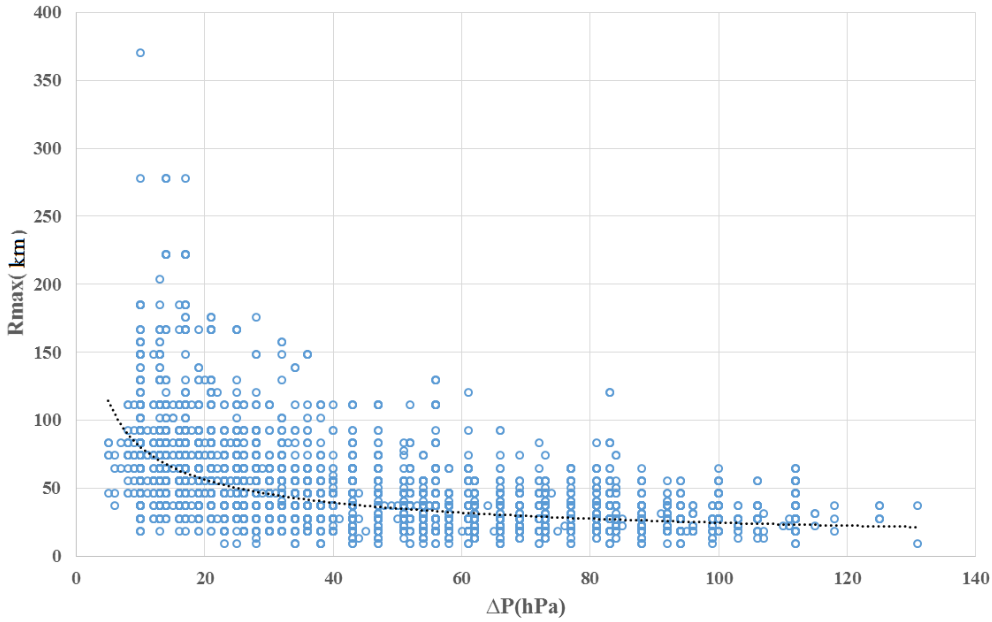


Fig. 10 The relation between the central pressure difference (ΔP) and the radius of maximum wind ($Rmax$)

3.4.4~~(4)~~ Astronomical tide

The coupling of the astronomical tide and the storm surge was performed for simulation of the total elevation and range of inundation. The monthly averaged high tide levels of the previous 19 years during June–October at the representative tidal stations in the study area were selected as the astronomical tide levels that were coupled with the storm surge at peak surge times in the local coastal area. The astronomical tide levels at Dongtou Station on the northern side of Pingyang County and at Pipamen Station on the southern side were 2.46 and 2.33 m, respectively. The larger value of 2.46 m was taken as the astronomical tidal level of the storm surge in the storm surge numerical model for the inundation simulation.

3.4.5~~4.5~~ Upstream flood runoff

The upstream flood is a factor required for numerical simulation of storm surges in estuary areas. Analysis of measured data and model studies indicate that the high-water level in an estuary area is controlled mainly by the astronomical tide and the typhoon-induced storm surge. The peak flow in an estuary has ~~no~~ obvious influence on the high-water level during the passage of a typhoon (Sun et al., 2017). The storm surge–runoff interaction in an estuary area increases the tidal level of a typhoon-induced storm surge, resulting in a larger hazard (Zheng et al., 2013). The larger the volume of runoff is, the greater the tidal level in the estuary area will be (Hao et al. 2018). The Feiyun and Aojiang rivers, located on the northern and southern sides of Pingyang County, respectively, are the main rivers that affect the level of flooding in Pingyang County. In this study, the superimposed upstream flood in the numerical simulation of storm surge was the average peak flows in the estuary areas of these rivers in the period of the selected historical typhoons during April-October, i.e., 1717 and 2348 m3/s for the Aojiang River and Feiyun River, respectively.

3.4.6 ~~4.6~~ S~~etting of s~~eawall collapse scenario

The seawall is an important barrier against storm surges and excessive overtopping of waves is the main cause of seawall collapse. Overtopping waves flush the seawall or the landward slope, forming a scour pit. As the scour pit grows, the upper structure of the seawall loses support and becomes unstable (Sun et al. 2015; Zhang et al. 2017). In the design of the majority of seawalls in China's coastal areas, the wave overtopping rate, which is determined based on tide level, wave height, and seawall structure, is used as a controlling indicator and as a parameter to judge whether a seawall will collapse. According to the results of physical model tests, seawall collapse will occur when the wave overtopping rate of the coastal seawall in Pingyang County exceeds 0.05 m3/s (Zhejiang Institute of Hydraulics and Estuary 2018). Once seawall collapse is determined in the numerical simulation, it will occur instantaneously without consideration of its process. After seawall collapse occurs in the numerical simulation, the ground elevation within the seawall is taken as the shoreline elevation, and the width of seawall collapse is determined by the wave overtopping rate at the representative point on the seawall. Each representative point represents a section of seawall.

~~4~~5 Calculation results

To further analyze the accuracy of the calculation results derived from the simulations, 22 representative reference points were set along the Pingyang County coast to obtain the desired data (~~see~~ Fig. 11). The calculated maximum ~~storm surge~~water level at each reference point for typhoons of different intensity is shown in Table ~~4~~5. It can be seen that for the eastern coastal area of Pingyang County, the maximum ~~storm surge~~water level of the representative points appeared near the radius of maximum wind speed on the southern side of the point of landfall of the typhoon. For the 915 and 925 hPa super typhoons, the typhoon track was moved from the reference position of Pingyang ~~(the center of Pingyang County)~~ southward by 25 km, reaching the Feiyun ~~River~~ Jiang estuary where the maximum ~~tidal~~ water level of 7.78 m appeared; by 30 km, reaching the Feiyun River estuary and the eastern coast of Pingyang, where the maximum ~~storm tide~~water level of 7.88 m appeared; and by 40 km, reaching the Aojiang River Estuary, where the maximum ~~storm surge tidal~~water level of 7.90 m appeared. For the 935, 945, and 965 hPa typhoons, the typhoon tracks corresponding maximum ~~storm surge track~~water level moved further southward as the radius of maximum wind speed increased. For example, the 965 hPa typhoon should move southward by 89 km from the reference position to reach the eastern coast of Pingyang, where the maximum ~~tidal~~ water level would ~~appear~~appear. Overall, the calculated maximum water~~tidal~~ level for the 925 hPa typhoon was approximately 0.17 to ~~–~~0.53 m lower than that of the 915 hPa typhoon, but approximately 0.29 to ~~–~~0.51 m higher than that of the 935 hPa typhoon. The calculated maximum ~~storm~~

~~surge tidal~~water level for the 945 hPa typhoon was approximately 0.28 to–0.5 m lower than that of the 935 hPa typhoon, but approximately 0.71 to –1.09 m higher than that of the 965 hPa typhoon.

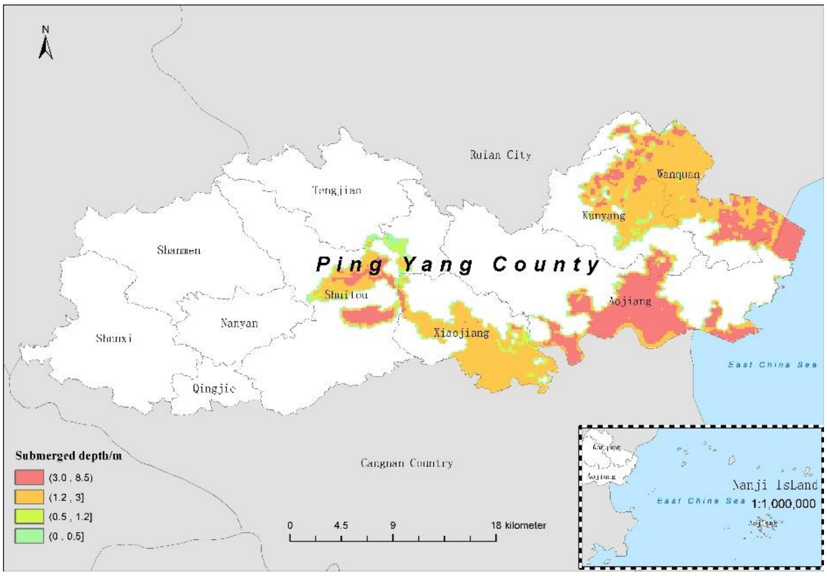
Fig.11 The reference points along Pingyang coast

Table ~~5~~4 Statistical results of maximum ~~tide~~ water level~~s~~ associated with unfavorable tracks of typhoons under different intensity scenarios

Reference points NO.	915hpa	925hpa	935hpa	945hpa	965hpa
1	7.61	7.28	6.90	6.48	5.53
2	7.59	7.26	6.87	6.46	5.51
3	7.60	7.24	6.85	6.43	5.48
4	7.62	7.24	6.83	6.42	5.46
5	7.65	7.25	6.82	6.40	5.44
6	7.70	7.27	6.82	6.39	5.42
7	7.79	7.32	6.86	6.41	5.42
8	7.85	7.37	6.89	6.44	5.44
9	7.87	7.38	6.90	6.45	5.44
10	7.88	7.38	6.90	6.45	5.44
11	7.88	7.38	6.91	6.45	5.45
12	7.87	7.36	6.90	6.44	5.44
13	7.91	7.39	6.94	6.47	5.46
14	7.58	7.17	6.72	6.27	5.37
15	7.66	7.30	6.84	6.38	5.40
16	7.66	7.43	6.95	6.48	5.45
17	7.79	7.56	7.06	6.58	5.52
18	7.90	7.69	7.18	6.69	5.60
19	7.81	7.62	7.15	6.68	5.68
20	7.64	7.47	7.05	6.64	5.72
21	7.44	7.27	6.91	6.57	5.75

22	7.36	7.05	6.76	6.49	5.77

Storm surge inundation was calculated for the unfavorable tracks corresponding to the five typhoon intensity scenarios. The storm tide levels caused by each unfavorable track were all the maximum storm surges of the 22 representative points around Pingyang. Therefore, it can be considered that the inundation superposition of these unfavorable tracks represented the maximum storm surge inundation range and the water depth distribution in Pingyang County associated with the typhoons of different intensity. The range of inundation in Pingyang County by the storm surges associated with the five typhoons of different intensity is shown in Figure. 126. It can be seen that the inundation range increased with the increase of typhoon intensity. Based on Figure. 126, Table 56 shows the statistical results of the maximum inundated area corresponding to the five typhoon scenarios. It can be seen that the area of Pingyang County inundated by the storm surge associated with the 915 hPa typhoon and the most unfavorableunfavourable track reached 233 km^2. The inundated areas included most parts of the town of Aojiang Town, eastern areas of Wanquan, north areas of Songbu, as well as parts of Kunyang and Shuitou, including administrative villages such as Qianjie and Jinmei.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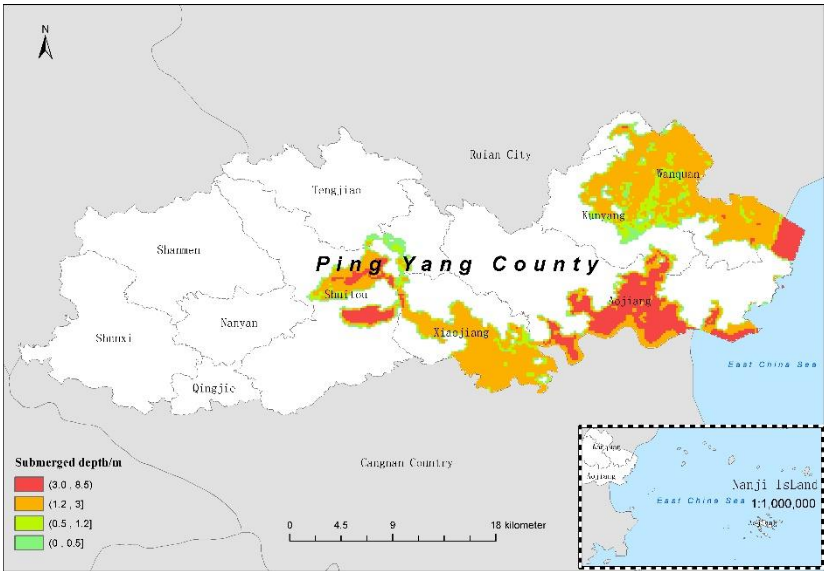
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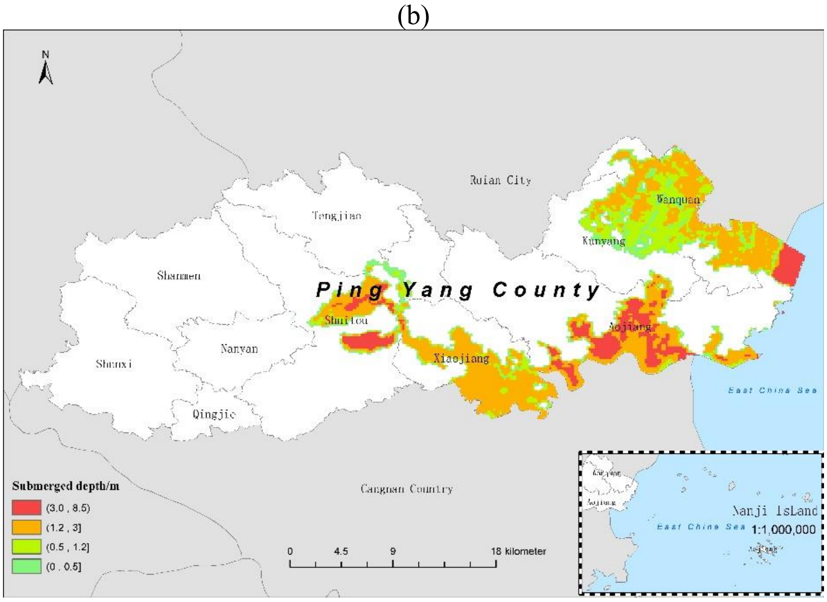
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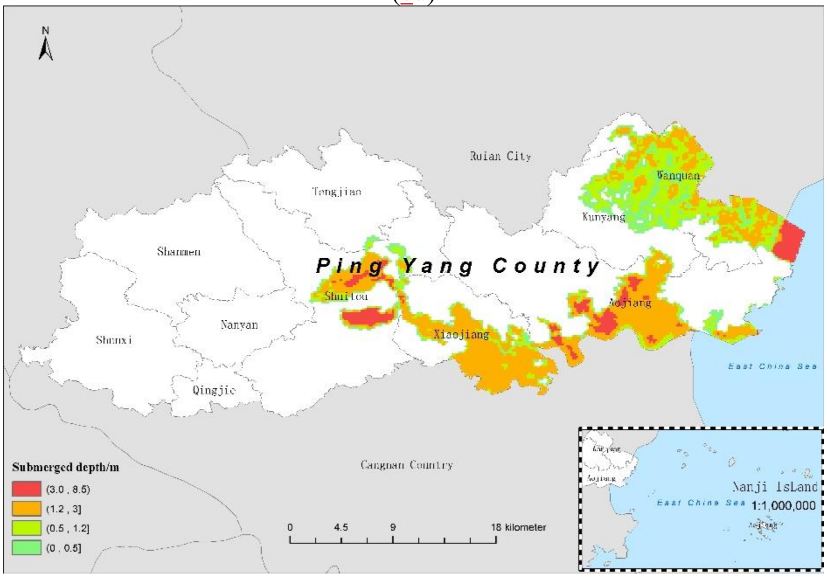

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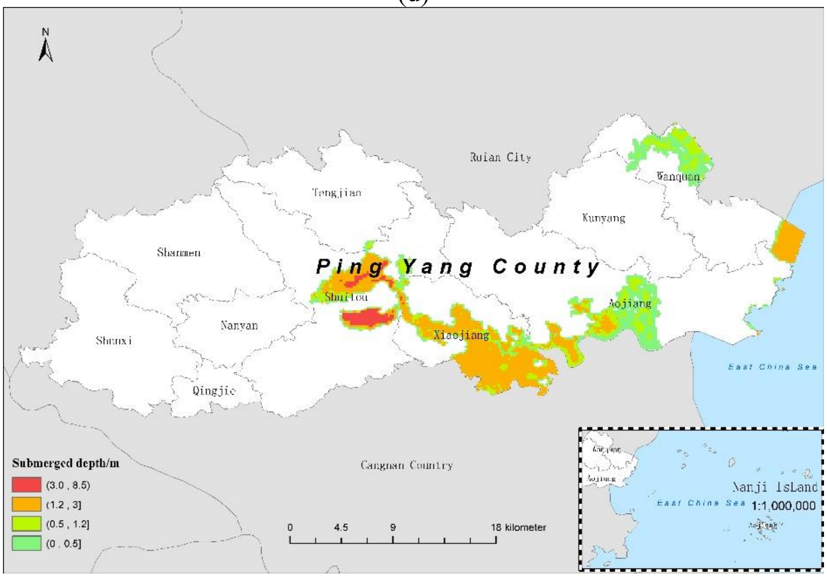

(e)

Figure. 512 Inundation range and water depth distribution of storm surges associated with typhoons of different intensity: (a) 915 hPa, (b) 925 hPa, (c) 935 hPa, (d) 945 hPa, and (e) 965 hPa

Table 56 Statistical results of maximum inundated area associated with different typhoon intensity scenarios (unit: km^2)

Typhoon Force	>3.0m Class I	1.2–3.0m Class II	0.5–1.2m Class III	Below 0.5m Class IV
915hpa	69.28	144.27	11.75	7.86
925 hpa	44.93	121.10	22.74	10.97
935 hpa	31.68	104.63	40.24	17.03
945 hpa	19.68	97.55	48.33	22.98
965 hpa	5.25	52.54	22.58	23.14

56 Conclusion and discussion

This study contributed to the methodology of storm surge inundation simulation caused by different intensities of typhoon. A high-precision numerical model for simulating storm surges was established and validated by observational data and field-surveying inundated areas after. Using these key parameters including typhoon tracks, radius of maximum wind speed, astronomical tide, and upstream flood runoff as driving factors, the inundation extents and depths in Pingyang County corresponding to the storm surges under different typhoon intensity scenarios were simulated in combination with the storm surge numerical model. The obtained results could serve as a basis for developing a methodology for storm surge disaster risk assessment in coastal areas. The study provides an insight into the spatial distribution of the areas potentially endangered by the typhoon related flooding. It can be helpful for further hazard and risk assessments for urban planning, emergency procedures and insurance.

A deterministic method for setting key parameters (e.g., typhoon track, radius of maximum wind speed, astronomical tide, and upstream flood runoff) under different typhoon intensity scenarios for calculation of inundated areas was proposed in this study. It considered Pingyang County as an example, but the developed method could be adopted in all coastal regions. A high-precision numerical model was established and validated for simulating storm surges within the study area. Using these key parameters as driving factors, the inundation range and water depth distribution in Pingyang County corresponding to the storm surges under different typhoon intensity scenarios were simulated in combination with the storm surge numerical model. The simulation results properly reflected the risk distribution attributable to storm surges in Pingyang County. The proposed method could provide reference for the establishment of a technical system for the assessment and zonation of storm surge risk in the coastal counties of China. The inundation range extent of a storm surge is related to many factors (Petroliagkis, 2018). In this study, the process of inundation is independent on the duration of the storm surge event, and the seawall collapse scenarios is simplified in a sudden, which could increase the inundation range of the simulated result. . The high wwater level in the towns of Shuitou and Xiaojiang in Pingyang County is mainly caused by the upstream flood of the Aojiang River. Consequently, the inundation situation in these two areas is directly related to upstream flood runoff. In this study, tThe impact of the upstream flood was only considered as the average of the flood peak flow during the storm surge in this study. The water level and inundation range areas caused by the large astronomical tide due to the superposition of the extreme flood scenarios might be more unfavorableunfavourable than the simulated storm surge with the superimposed average of the flood peak runoff, which might result in uncertainty in the calculation results. In our next study, Wwe will further analyze the quantitative response relationship between typhoon intensity at landfall and upstream flood runoff, and propose a quantitive method for setting flood runoff upstream of the estuary area in the further research.

This paper presents a deterministic method for setting key parameters under typhoon intensity scenarios assuming that these factors (e.g., typhoon track, radius of maximum wind speed, astronomical tide, and upstream flood runoff) are independent.; HHowever, any correlation between these parameters is ignored. The occurrence probability of parameter combinations is difficult to evaluate. The joint probability method is an efficient way to determine the base flood elevation due to storm surge (Yang et al. 2019), and the joint probability among these factors could be established (e.g., using the Copula method) to calculate the occurrence of extreme storm surge events.

This study contributed to the methodology of quantitative assessment of storm surge hazards for coastal counties. If combined with a vulnerability curve between the loss ratio of typical exposure influenced by storm surges and the water depth induced by flooding in coastal areas, a quantitative storm surge risk could be evaluated in future research. The results of a quantitative assessment of storm surge risk could provide a theoretical basis for urban planning, development of emergency evacuation procedures, and disaster insurance.

Data availability: All data used during the study are available from the corresponding author by request.

Author contribution: Shi prepared the manuscript with contributions from all co-authors and set the key parameters; Yu, Chen, Wu and Cheng performed the numerical simulation; Guo analyzed the inundated results; Sun provided the tidal observational data; Zeng conducted this research and designed the experiments.

Competing interests: The authors have declared that no competing interests exist.

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